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AN INVESTIGATION OF AUTOMATIC RESTRAINT AND BODY POSITIONING TECHNIQUES

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13. ABSTRACT

A unique test apparatus was designed, fabricated and tested which will permit the study of performance limits of automatic restraint and body positioning systems. The program was initiated by a parametric analysis that established the relations that exist between those parameters that dictate the efficacy of an automated system. The study was followed by an investigation of design criteria related to escape sequence timing, optimum positioning, cockpit interface and human tolerance. These data were compiled and used with new principles and techniques of retraction and restraint and led to the design of an automatic test device. The fabricated device is a hydraulically operated system capable of retracting any body segment over its extreme range within 0.100 seconds. The force and stroke length available will permit evaluation of retraction systems at levels near or exceeding current exposure limits.

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Ejection Seat Escape Capsule Ballistic Inertial Reel Leg Restraint Arm Restraint Lap Belt Retration						

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FOR THE COMMANDER

HENNING E. VON GIERKE
Director
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PREFACE

The research covered in this report was performed under Air Force Contract F33615-69-C-1099 and in support of Project 7231, "Biomechanics of Aerospace Operations," Task 723106, "Impact Exposure Limits and Personnel Protection Criteria." This contract was awarded to Beta Industries, Inc., on 15 October 1968 and completed on 30 June 1970. This effort was initiated with Commander's funds.

The Air Force Program Monitor was Mr. James W. Brinkley of the Impact Branch, Biodynamics and Bionics Division of the Aerospace Medical Research Laboratory, Aerospace Medical Division of Air Force Systems Command, Wright-Patterson Air Force Base, Ohio.

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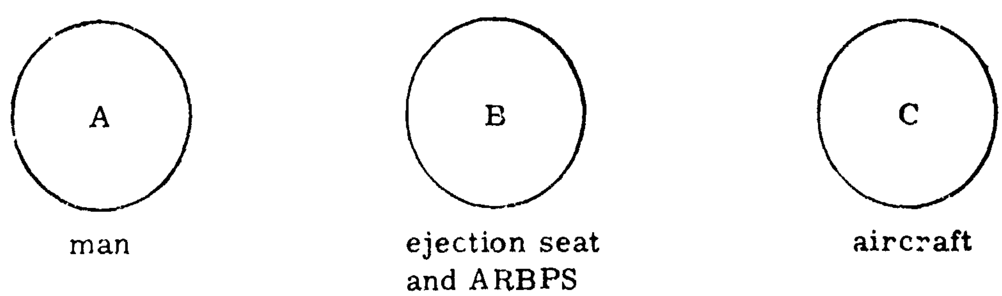
SECTION I

INTRODUCTION

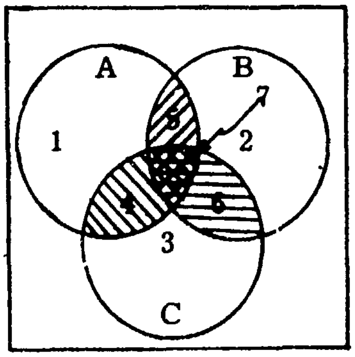
The basic problem being considered by this research effort is the escape of crewmen from stricken aircraft. In the early days of aviation, escape was accomplished by simply climbing out of the damaged vehicle; however, as flight speeds increased ejection type escape systems became necessary. Today as aircraft performance is increasing through higher speeds, contour flying, etc., the elapsed time from the instant the pilot recognizes the need for escape to the point of no survivable escape is becoming precariously small. In addition, the severe accelerations that can be encountered after an aircraft becomes uncontrollable may incapacitate a crewman so that he cannot position himself for ejection.

The use of automatic positioning and restraint devices offers the possibility of reducing the ejection sequence time, assisting the air-crewmen in overcoming the effects of acceleration, and protecting them from flailing injuries caused by windblast. While this is a promising concept it also carries many potential hazards and disadvantages. For example, rapid retraction of the extended legs may cause a disabling injury. Another consideration would be the encumbrance caused by the attachment or equipment necessary for automatic positioning and restraint. There are many questions that must be answered and many trade-offs that must be considered before a truly meaningful design of such an automatic system can be performed.

In treating this problem there are three systems to be considered. These systems are the man, the ejection seat and automatic body positioning and restraint system, and the aircraft. Each of these systems is represented below by a circle. Let circle A represent the man, circle B represent the ejection seat and the automatic body positioning and restraint subsystems, and circle C represent the aircraft.



The relationship between these systems can be graphically represented as shown on the following page:



This figure contains seven different areas that represent the different degrees of dependency between the three systems. For example, area 1 can be described as those properties of A that are not influenced by or do not influence the properties of B or C. Since A represents the man such a parameter for the problem under consideration would be race, color of eyes, religion, etc. In terms of Boolean algebra each of these areas would be described as follows:

Area	Area	Description
1	$A \cdot \overline{B} \cdot \overline{C}$	(that is all of A that is not B or C)
2	$B \cdot \overline{A} \cdot \overline{C}$	
3	$C \cdot \overline{A} \cdot \overline{B}$	
4	$A \cdot C$	(i.e., that area included in the "intersection" between A and C)
5	$A \cdot B$	
6	$B \cdot C$	
7	$A \cdot B \cdot C$	(i.e., that area included in the "inter section" between areas A, B and C)

where: $\cdot$ is called "intersection", and $\overline{A}$ is "not A", etc.

Obviously areas 1, 2 and 3 are not of concern to the problem at hand because these areas include parameters that are unique to each system itself and do not have any influence on the total system. Similarly areas 4 and 6 are not of interest since area 4 includes only those parameters that relate to the man and aircraft but not to the escape system. An example would be that man is related to the aircraft because he must fly it. Area 6 covers those items that are common to the aircraft and the seat such as the orientation of the instrument panel to pilot's seat.

This, then, narrows the problem down to areas 5 and 7. Area 5 contains all parameters that relate to the interfacing between the man and the escape system, and area 7 contains all parameters in the above category that are also influenced by aircraft parameters. An example of a parameter in area 5 would be the mechanical characteristics of the surface on which the body segments may impact when retracted, whereas an example of a parameter in area 7 would be aircraft acceleration that must be overcome to position the crewman.

The first task of this research effort was to establish the list of the parameters that are pertinent to the design of automatic body positioning and restraint systems, and then to develop the relationship between these parameters.

After these parameters were identified and their relationship defined the next step was to quantify the parameters with respect to current and future systems. These parameters were divided into two categories called design criteria and performance limits. Design criteria are those parameters that are unique to the design of a specific subsystem, whereas performance limits are those parameters that are independent of system design or absolute in that they are the maximum values to which a system can be designed without being a potential hazard to the crewman.

The next logical step was then to develop concepts and establish new principles and techniques of body retraction and restraint. These, along with examination of current concepts and exposure limits, establish the criteria for the desired test device. Preliminary designs and the evaluations of them have been presented in order to establish the reasons for selecting the fabricated design. The test apparatus that was fabricated and tested does provide adequate capability to explore automatic retraction and restraint to levels previously not attempted under controlled conditions.

SECTION II

PARAMETRIC STUDY

PARAMETRIC RELATIONSHIPS

The objective of this portion of the research effort was to conduct a study of the parameters that are involved in the design of automatic body positioning and restraint equipment and to develop the interrelationships between these parameters. In conducting studies of this nature it is necessary to direct the work in such a manner that all of the parameters are identified and to insure that none are omitted by oversight. To insure that these objectives would be met the problem was approached with the flow diagram technique. Using this method and starting with basic design information the logic for designing a piece of hardware is mapped out in a manner similar to the diagramming of a computer program. As the mapping progresses the need for new parameters becomes readily apparent and the relationship between all of these parameters is shown symbolically by the interconnecting lines of the flow diagram.

During the performance of this portion of the effort a preliminary parameter flow diagram was prepared for the various segments of the body. A review of these diagrams revealed a great similarity between all diagrams and indicated that parametric relationships could be represented by one general flow chart. An abbreviated form of this parameter flow chart is presented in figure 1.

Reviewing figure 1 it is immediately obvious that all of the retraction and restraint subsystems must be considered simultaneously. First it is necessary to obtain timing data on each subsystem as is indicated by the first level of the diagram. The time information is considered with sequencing data to determine the overall system performance and to optimize the designs of the total system. At this point input data to the sequencing block of the diagram is again separated into the individual subsystem categories. Finally this data is used to perform the more detailed subsystem design which includes the consideration of restriction forces, retraction kinematics, and the biological consequences of retraction.

The complete flow diagram of the parametric relationship is presented in figure 2, and will be discussed thoroughly in the following paragraphs. First, note that the diagram is separated into three parts by the two lines designated as Common Input Lines. Above and below the center section the subsystems are treated individually; however, in the center section the interrelationship between these subsystems in the total system is considered. In this diagram only one subsystem is presented in the top and bottom sections; however, it should be realized that each subsystem is related in a similar manner.

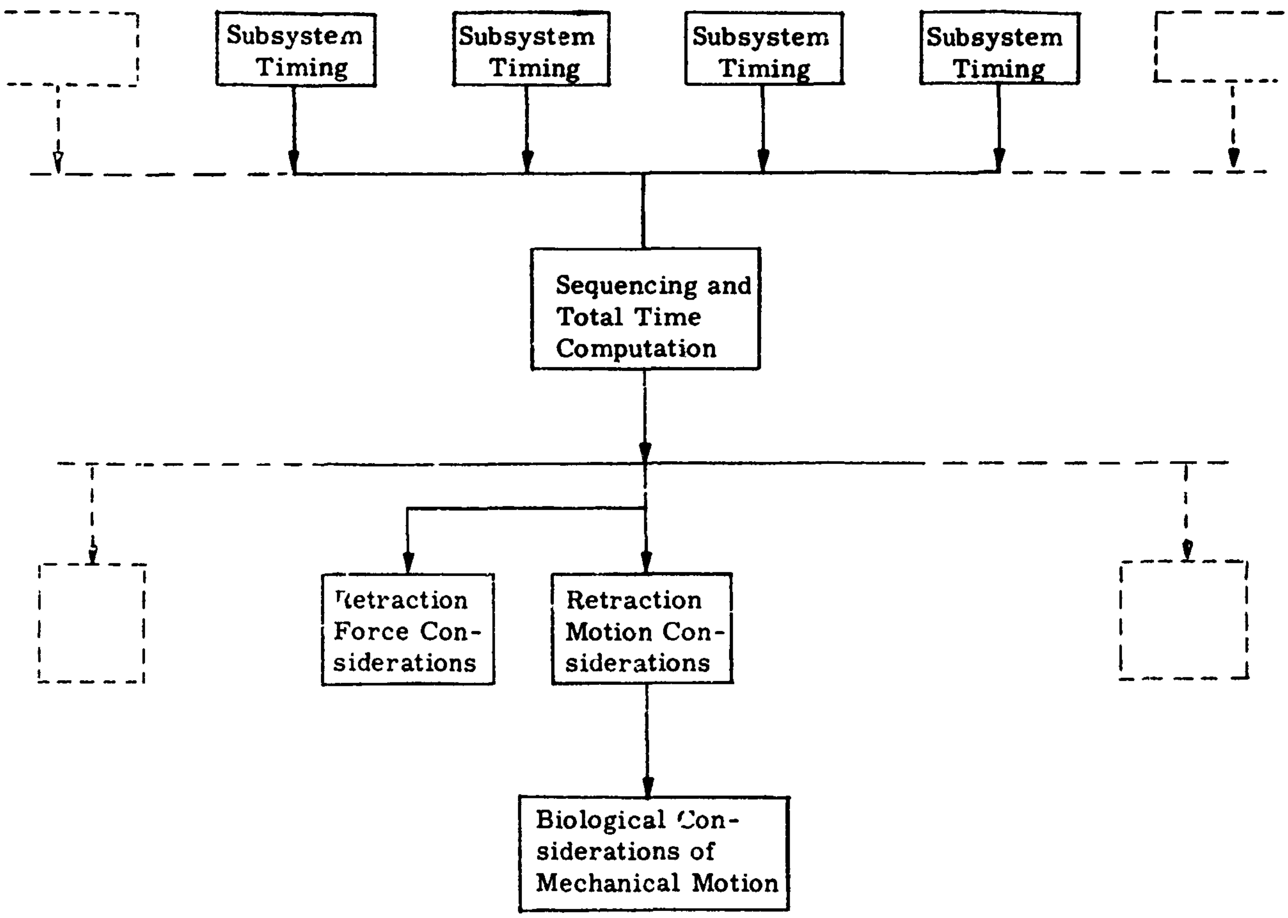


Figure 1. Parameter Flow Chart (Abbreviated)

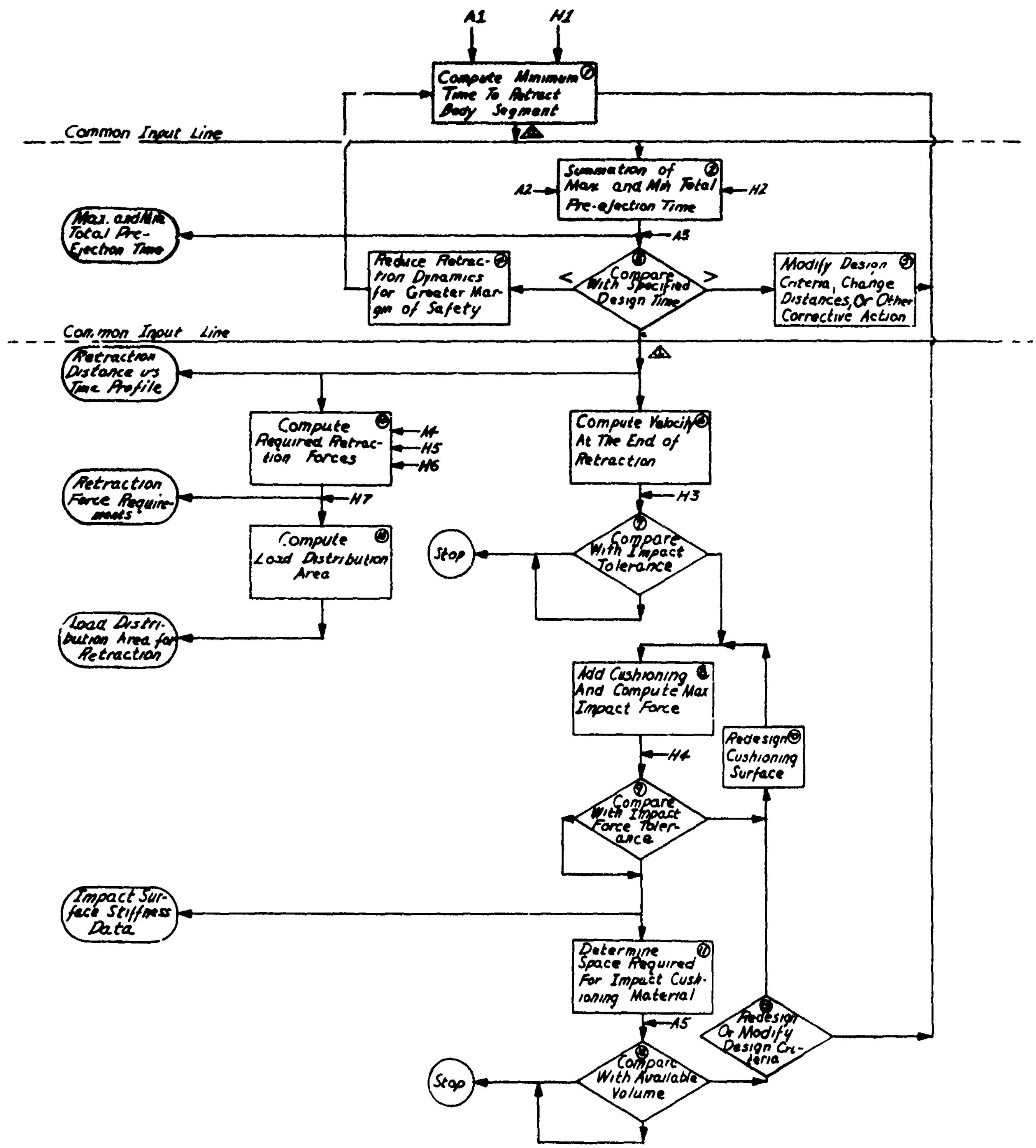


Figure 2. Parametric Flow Diagram

Assuming parameters A1 (retraction distance) and H1 (body segment tolerance to mechanical motion) are known, it is possible to compute the minimum time in which the body segment can be retracted to required distance. This time (1) is then directed to the common input line as are the minimum times computed for all other retraction subsystems. All of these times are then used to compute the total prepositioning time (2). However, it is not possible to simply add these times because there is an actuation sequence that must be considered. Therefore, input H2 (optimum retraction sequence) must be known to compute the total prepositioning time.

Since most retractors are powered by pyrotechnic actuators there is considerable variability in their performance (A2); therefore, this must also be considered when computing the total prepositioning sequence time. If the minimum time is specified by human tolerance then the maximum time is specified by the variability of the actuator performance.

At this point it is necessary to compare the minimum prepositioning time with A3 (desired prepositioning sequence time) as is indicated by step (3). If the minimum time is less than the desired time the retraction dynamics can be reduced in the critical areas (4) to obtain a greater margin of safety. Similarly, if the maximum time is greater than the desired time some corrective action must be taken as indicated in step (5).

After establishing the minimum retraction time for each subsystem by the above procedure it is necessary to investigate the interrelationship of the force, kinematic, and biological aspects of each individual subsystem. These computations only need to be performed for the minimum time because this will be the most severe case. Knowing the required retraction distance (A1) and the body segment tolerance (H1) it is possible to compute the velocity of the body segment at the end of retraction, which is shown as step (6). If an acceleration profile other than A1 is dictated by the actuator this should be used to compute the velocity; however, in no case should this acceleration exceed A1. This velocity will also be the velocity at which the body segment impacts the support structure and therefore must be compared with the body segments tolerance to impact on a hard surface (H3) as is indicated by step (7). If the impact velocity is less than tolerance then the design is acceptable. However, if it is greater than tolerance it is necessary to provide an energy absorption material on the impact surface to attenuate the impact forces. In step (8) the forces generated upon impact with the cushioned surface are computed and then compared with body segment tolerance to impact force (H2) in step (9). If the impact forces are tolerable the process continues to step (11); however, if they are too severe the cushioning must be redesigned, step (10), and the process repeated until an acceptable impact surface is selected. Upon selecting an acceptable impact surface it is necessary to determine if it is possible to package the design in the available volume (A5). This process is represented by steps (11), (12), and (13) which are self explanatory.

In addition to the kinematic aspects of the design it is also necessary to treat the force considerations of the subsystem design. Step (14) involves computing the force required to retract the body segment and requires the same acceleration and distance data used to compute velocity in addition to the aircraft acceleration environment (A4), body segment mass and inertial properties (H5) and body segment resistance to motion (H6). The next and final step is to determine the loading area necessary for distribution of the retraction forces. This is completed in step (15) in which the computed retraction force is divided by the body segment tolerance to concentrated loading (H7).

PARAMETER DISCUSSION

The above discussion demonstrated the technique used to establish parameters necessary for the design of automatic body positioning and restraint systems and to develop the relationship between these parameters. This process identified five aircraft design parameters (A1 through A5) and seven human design parameters (H1 through H7) that are required for each body segment that requires retraction and restraint. As would be expected there are parameters that become apparent but that do not lend themselves to parametric flow diagram presented in figure 2. Because of their peculiar nature these parameters are considered as additional design criteria and will be considered in the following section. However, in the following paragraphs the design parameters defined in the previous section will be discussed in detail.

The design parameters identified with an A prefix in figure 2 fall in logic area 7; i.e., they are parameters that involve the aircraft, the body positioning and restraint system, and the crewman. There were five such parameters identified; however, several of these are general terms in that they have a different value for each body segment being retracted.

The parameters identified in figure 2 with an H prefix can be generally classified as human design criteria. However, further examination of figure 2 shows that some of these parameters are used as test statements whereas the others are used as inputs for various computations. The former group consists of parameters that indicate man's tolerance to severe environments and thus serve to establish the limits of performance for the retraction system. Therefore these parameters will be further identified as performance limits. The latter group of parameters includes biodynamic data that are necessary to make meaningful computations necessary for the design of retraction and restraint subsystems. These parameters will be called human design criteria.

Aircraft Design Criteria

Retraction Distance (A1)

The first design parameter required is the distance that the body segment must be retracted. This term is self explanatory and the values are readily obtainable from anthropometric data and the cockpit configuration.

Variability of Actuator Performance (A2)

This parameter relates to the performance of the actuators used to power the retraction systems. Normally these actuators are pyrotechnic devices and as such have variable operating characteristics depending on temperature and other parameters. These devices are capable of powering retraction systems in the time range of 0.5 seconds yet these retraction times may vary several tenths of a second over the temperature range of -65°F to 200°F. Therefore, this variability must be considered in the design of a system.

Desired Prepositioning Sequence Time (A3)

This parameter is one of the initial design criteria that should be specified for each aircraft. Knowing the aircraft and its performance envelope and the nature of the crisis, it is possible to estimate the time that is available for escape. However, it would seem expedient in future aircraft to reduce this term to the minimum time possible without causing injury to the crewman to cover the greatest variety of eventualities. Of this total time a certain portion must be allotted to the prepositioning of the crewman before ejections, but it is important to realize that prepositioning does not necessarily have to be completed before the ejection sequence is initiated. Indeed it may be feasible to be completing retraction as the catapult is being fired but before any significant ejection seat movement has occurred. On the other hand, this requires accurate sequence timing and may be beyond the state-of-the-art for pyrotechnic devices.

Aircraft Acceleration Environment (A4)

In the design of a retraction device it is necessary to know the forces that are involved so that the retraction mechanism and the actuator can be properly sized. The forces required to retract a body segment are composed of three components. One of the more significant components is due to the acceleration environment being imposed on the crewman during the time retraction occurs. Therefore, the design of a retraction system requires a knowledge of the maximum acceleration environment that the aircraft will be sustaining at the time of body prepositioning.

Volume Available for Escape Systems (A5)

This parameter relates the design of an ejection system to particular vehicle in which it will be used. This term is important in that it places bounds of practicality on the size of a given system. This parameter is largely dictated by each aircraft; however, there are established minimums that are specified minimums in the "Handbook of Instructions for Aircraft Design."

Performance Limits

The following is a discussion of the performance limits identified in figure 2. Each of these parameters is presented in the general term of body segment; however, they apply to any portion of the body that is being retracted such as the limbs, torso, pelvis, or head.

Body Segment Tolerance to Mechanical Motion (H1)

In the retraction of any portion of the body it is necessary to accelerate and move this segment through the application of some mechanical force. Needless to say, the short times permitted for retraction imply that the motion of the body segments will be violent. However, the motion cannot be so severe that it causes injury to the crewman. For example, rapid retraction of the upper torso can cause damage to the spine. Therefore, in the design of these retraction systems the tolerance of the various body segments to mechanical motion must be known. This data will most likely take the form of acceleration data.

Body Segment Tolerance to Impact on a Rigid Surface (H3)

In the retraction sequence the body segment is moved through the retraction distance into the desired ejection position. However, the body segment is moving at some finite velocity when the retraction distance reduces to zero. At this instant the body segment impacts with the structure that will support it during the ejection phase. The inherent danger is that this impact may cause injury to the crewman; therefore, the designer must know the threshold of impact injury. If the impact is below the tolerance level the designer does not have to provide for impact protection. If it is greater than tolerance the designer must incorporate a cushioning surface to attenuate the impact. Therefore, the designer first needs to know the body segment tolerance to impact on a rigid surface.

It seems apparent that this parameter can best be defined in terms of impact velocity. Velocity is chosen here because the velocity of a body segment immediately prior to impact is readily measured, whereas measurement of acceleration is rather ambiguous and is dependent upon the mounting of the instrumentation, the frequency response of the instrumentation, and the stiffness of the impacting surface.

Body Segment Tolerance to Impact Force (H4)

If the velocity of the body segment at impact exceeds the tolerance level it is necessary to add a compliant material to the impact surface. This does not decrease the impact velocity but the elastic nature of this material permits the body segment to decelerate over some finite distance and thus distributes and reduces the impact forces.

It appears that the most meaningful term to define this impact tolerance is a maximum force for any given impact area. This term is

recommended for establishing impact tolerance on a cushioned surface because as indicated earlier the impact acceleration is difficult to understand and measure and because the velocity of impact is meaningless due to the compliant surface.

Human Design Criteria

The discussion presented below describes those parameters identified in figure 2 that are considered to be human design criteria. These differ from the other human body parameters in that they are biodynamic properties such as moments of inertia rather than tolerance limits. Therefore these parameters are used to make design calculations and not to indicate the limits on the performance of a system.

Optimum Retraction Sequence (H2)

This parameter relates to all the body segments simultaneously in that it is a measurement of the order in which the many segments of the body should be retracted. For example, it is known that severe shoulder retraction can cause the limbs to flail. Therefore, if shoulder and limb retraction were to occur simultaneously the physical stress on the limbs could conceivably be much greater than if these segments were retracted at different times. Therefore, this sequencing parameter should be available to the designer as a design criteria and also as a tool to compute the total prepositioning time.

Body Segment Mass and Inertial Properties (H5)

To compute the force requirements for retraction it is necessary to know the mass and the inertial properties of the human body. This data enables the designer to compute the forces required to overcome the inertial resistance of the body segment. This force is then added to the force required to overcome aircraft acceleration and joint resistance. The total force is then used by the designer to size the actuators and structural members.

Body Joint Resistance to Flexing (H6)

When any of the body segments are positioned by some external forces there is an inherent resistance offered by the joints of the human body. As indicated in the above paragraph these data are necessary for sizing the components of the retraction system.

Body Segment Tolerance to Concentrated Loading (H7)

The retraction of any segment of the human body requires that a mechanical force be applied to the segment. The designer must apply

this force in such a manner that it does not cause unreasonable pain or injury. Therefore, it is necessary for the designer to have data on the load carrying capability of the various body segments so that forces necessary for retraction can be distributed in a manner that is acceptable and tolerable.

ADDITIONAL DESIGN CRITERIA

As discussed earlier the parametric flow diagram shown in figure 2 identifies most of the design parameters that are pertinent to retraction and restraint subsystems. However, there are also several subtle parameters that were not identified in figure 2 but should be considered. These parameters are referred to as additional design criteria and will be presented in detail below.

Residual Lockup Force

The function of an automatic positioning and restraint system is to position a crewman in the most desirable ejection position and to restrain him in this position. The purpose of the positioning function is to insure that the ejection accelerations are directed correctly, to prevent the limbs from striking the aircraft during ejection, and to reduce any misalignment of the center of gravity of the seat/man combination. However, the purpose of the restraint action is to hold the crewman and his limbs in a supported position during the ejection and windblast phases and thus prevent any flailing injuries. The problem being considered in this section is the restraint of a body segment after retraction has occurred.

Restraint is normally accomplished by mechanically locking the retraction system at the end of the retraction stroke. When this occurs the body segments are somewhat compressed due to the forces being applied by the retraction system. As a result, when lockup occurs there is a residual force being statically applied to the occupant. This residual lockup force must be seriously considered in the design of the complete system because they must be sufficient to hold the crewman in position and to protect him from flailing. However, it is equally important that this residual force is not large enough to restrict the man's breathing, cut off circulation, or cause some other debility.

Encumbrance

The retraction sequence requires that the crewman's body segments be forceably placed into a desirable ejection position. In order to apply these forces to the body it is necessary to have some attachment to the crewman or a means of grasping him automatically. For example, cable type foot retractors have several disadvantages from the encumbrance viewpoint. The cables do not permit the crewman to cross his feet, they

could become entangled and finally they require release before rapid ground evacuation. Under normal flight conditions this equipment may be bothersome to the crewman or restrict his performance. The encumbrance parameter is an evaluation of the restriction on the pilot's performance due to the retraction systems. Unfortunately this is a qualitative parameter and cannot be quantified. The only way of comparing one system with another is to evaluate them on a subjective scale using the shirt sleeve environment as a base reference.

Ease of Release

Another objective parameter that must be considered as an additional design criteria is the ease with which a crewman can release himself after retraction.

The restraint system selected must provide a means of separating the man from the seat without undue difficulty. At low level ejection in particular, the man must be separated from the seat quickly to reduce the time required to initiate the actuation of the personnel parachute, if that type of system is used. The paradox of the restraint system is that it is required to hold the man rigidly against a structural seat during an extreme acceleration and yet release him completely a moment later. It must have structural strength and mechanical operation and yet not consist of mechanical, hard, structure that inhibits his freedom after use of the system. This parameter can be evaluated only after a type of restraint has been selected. Do the components of the restraint all attach to the seat, are some integral to the flight suit, are they separable from both seat and man? For a particular system it is possible to evaluate whether or not freedom can be easily achieved

Effectivity of Restraint

A final overview of the total system of retraction and restraint subsystems should yield an evaluation of the effectivity of restraint systems. This overview should consider all of the advantages and disadvantages of the system with respect to the original design requirements. The system should retract and position the various body segments; it must restrict motion of the body segments to insure that there is no relative motion between the seat and man, or that the motion is controlled to attenuate the response; it must be acceptable to the crewman, it must be easy to release, etc. Unfortunately, this parameter can only be a subjective quantity and will vary from evaluator to evaluator. Nevertheless, this final scrutiny is necessary to insure the success and acceptability of the design.

Impact of Limbs on the Torso

In the development of the parametric flow diagram it was assumed that the limbs would be retracted back against the ejection seat surfaces.

However, this procedure need not always be the case. For example, the North American A-5 escape system retracts the arms back against the chest. In this case one must be concerned with the possible injury to the arms and the chest. Therefore, it should be stated that the designer must always be aware of all the consequences of a proposed design and cannot limit his attention to a fixed set of parameters such as those identified above.

Total System Weight

Another parameter that looms very large in aircraft design problems is system weight. Indeed this parameter is of such concern that it may force the incorporation of a less desirable system to meet weight requirements. An example could be the comparison of the leg retraction system used in the A-5 and the system used in the F-104. In the first case the legs are retracted by lifting the knees and grasping the ankles with ballistically driven mechanical linkages. These devices do not require any direct attachment to the pilot and are very advantageous from the encumbrance viewpoint; however, there is considerable weight involved. The F-104 system uses cables attached to the pilot's heels and these cables are ballistically retracted. This system is much lighter than the A-5 system, but the cables can be bothersome to the pilot.

Obviously, the A-5 system appears to be the most desirable when considering encumbrance; however, such a system probably would not be used in a light aircraft such as the F-104 because of the weight penalties.

SECTION III

REVIEW OF EXISTING RETRACTION AND RETENTION SUBSYSTEMS

Some of the most advanced aircraft have included the use of automatic body positioning and/or restraint devices. The initial requirement for these devices developed from the use of encapsulated seats, downward ejection seats, and ejection sequencing that would permit the pilot to eject a crewman without his prior knowledge. The more recent prepositioning systems were incorporated to overcome adverse accelerations acting on the crewman during ejection and to provide protection against flailing injuries caused by windblast.

The design and development of most of these systems was unrelated and was conducted independently. However, the successful use and performance of these systems offers a source of information that should be compiled and documented. These data can serve as a basis for the design and development of future positioning and restraint systems. A survey of the aircraft industry and the Armed Services was conducted to determine the design criteria used to develop these devices and the performance characteristics of the resulting equipment. The data gathered during this survey were extracted from military and contractor specifications, test data, developmental reports and other similar forms. Since many of the systems were developed before applicable specifications were written there is scant quantitative data available on some of the devices. The following subsections present a compilation of the data gathered on systems for retracting the shoulder, the legs, the arms, the pelvis, and the head. Undoubtedly there are some experimental systems or concepts that are not described because they were not discovered or because they were of a proprietary nature. Nevertheless, the data presented are considered to be as complete as possible. It should be pointed out that the compilation of these data would not have been possible without the assistance of those organizations that chose to cooperate with the study. These groups graciously provided data through technical conferences, test reports, design specifications, test records, etc.

UPPER TORSO RETRACTION AND RESTRAINT

The upper torso is the portion of the body that has received the most attention with regard to automatic positioning and retention. Apparently the B-58 capsule was the first system to use power retraction of the upper torso, and now it appears that nearly all ejection seats will be retrofitted to incorporate such a power retraction device.

Shoulder restraint and retraction has been accomplished by incorporating a powered retraction feature in the inertia reel that is attached to the shoulder harness. At the initiation of the ejection sequence, a cartridge

actuated device powered by a cartridge or a gas generator provides the energy to retract the webbing straps, pulling and cinching the occupant's shoulders against the seat back. In this configuration the power retraction adds an additional capability to the ejection system but does not compromise any of the previous functions should it fail to operate.

During the survey it was discovered that these retraction systems are ever evolving and that the compilation of performance data on all of these systems was virtually impossible. However, it was determined that these systems operate nominally within specifications that have been recently written by the Air Force and the Navy. It was also discovered that the development and manufacture of these devices was limited to six organizations. These are Pacific Scientific Incorporated, Tally Industries, Martin-Baker Aircraft Company, Hardman Aircraft (under license to McDonnel-Douglas), Universal Propulsion Company (under license to Space Ordinance Systems), and the Frankford Arsenal.

In the following section the pertinent paragraphs from present military specifications will be presented. Following this will be descriptive data on those systems that could be readily identified and for which data were available.

Applicable Military Specifications

The specifications of the inertia reel itself have no role in the automatic positioning of crewmen. The military specifications relating to the design parameters of the powered retraction devices are as follows:

MIL-S-9479A (USAF); 27 November 1967

Seat System, Upward Ejection, Aircraft, General
Specification for

Paragraph 3.4.2.8.3.1 Powered Upper Torso Restraint - The inertia lock reel mechanism shall have a powered retraction feature which shall automatically position and restrain the seat occupant against the back of the seat as a pre-ejection function. The powered retraction feature shall be capable of positioning the seat occupant through 0 to 18 inches of travel. It shall be capable of taking up a load of 0 to 800* pounds within 0.3 second maximum of 70°F (0.4 second maximum at -65°F). The reel-in velocity shall be limited to a maximum of 12 feet per second with the nominal velocity being 9 feet per second. The maximum total load applied to the seat occupant after the reel has positioned the occupant shall not exceed 100 pounds. The maximum acceleration and rate of onset of acceleration shall not exceed 20 g and 500 g per second, respectively.

MIL-D-81514A (AS) (Navy); 21 February 1967
Device Restraint Harness Take-Up, Inertia Locking Power -

Retracting: General Specification for

Paragraph 3.6.1.2 Power Retraction - As installed and used in the aircraft and in conformance with the applicable seat specification, the powered retracting function of the device, when initiated during the pre-ejection sequence, shall position and forcibly restrain subjects equipped with the applicable survival equipment. The total residual strap force following full power retraction shall not exceed 100 pounds. The device. when installed in the seat, shall be capable of performing this function when the seat occupant is subjected to a resisting acceleration of 2 g. Actuation of power retraction shall cause automatic locking of the stowage/take-up mechanism. The locking mechanism shall remain locked unless cycled in accordance with 3.5.2.7.

Paragraph 3.6.1.2.1 Retraction Time - The maximum time for retraction of the strap/cable from full extension or any part thereof, from the time that the gas generator firing mechanism is actuated until full retraction is accomplished, shall not exceed 0.3 seconds at ambient or high temperature (70°F and 160°F) for the conditions described herein. Similarly, the maximum time of retraction of the strap at full extension or any part thereof shall not exceed 0.4 seconds at -65°.

Paragraph 3.6.1.2.2 Velocity - For any personnel restraint harness takeup strap/cable extension within the temperature range and conditioning specified herein, at the point of attachment to the personnel restraint harness. The maximum velocity of the takeup strap/cable shall not exceed 9 feet per second measured over the 0.20 second interval immediately prior to shoulder contact with the seat.

MIL-S-18471C (AS) (Navy); 1 April 1968
Seat System, Ejectable, Aircraft, General Specification for
Paragraph 3.3.1.1.6.1 Shoulder Restraint Takeup Mechanism - The ejection seat shall incorporate an inertia-locking shoulder harness takeup device having a powered retraction feature to automatically place the seat occupant in the best position for withstanding the loads imposed upon him by (a) windblast during canopy removal, (b) seat positioning (if applicable), and (c) seat boost. The device shall conform to MIL-D-81514. Full, powered retraction of all crewmen shall occur prior to the jettisoning of the cockpit canopy to provide them maximum protection from windblast. The shoulder harness bearing point on the ejection seat shall be located so that the angle between the crewman's midaxillary line and the line the shoulder makes to the shoulder harness bearing surface on the crewman's shoulder shall be a minimum of 90 degrees, as shown on BuWeps Dwg. 65A136H1. In those seats in which the seat adjustment is accomplished by means of independent movement of the seat bucket, the location of the ejection seat shoulder harness bearing point shall be determined by a crewmember with a 3rd percentile sitting shoulder height and sitting eye height with his eyes at the design eye level. In those seats in which the seat adjustment is accomplished by means of movement of the entire seat, the location of the ejection seat shoulder harness bearing point shall be

determined with a crewmember with a 98th percentile sitting shoulder height and sitting eye height with his eyes at the design eye level. Forces imposed by the automatic takeup mechanism shall not injure the seat occupant. In addition, the shoulder restraint system must provide adequate lateral restraint of the seat occupant. A manual lock-unlock control for the takeup mechanism shall be provided on the left side of the seat. The design and placement of the control shall facilitate crewman operation of the control.

General Dynamics - B-58 Escape Capsule

The upper torso restraint harness is configured as shown in figure 3 (Ref 1). The quick release mechanism joins the left-hand and right-hand shoulder and lower strap combinations. A chest pad, located between the harness links and beneath the quick release mechanism, provides for crew comfort.

(a)

Reel Inlet Pressure	Temperature	Retraction Time
850 psi	-65°F	0.60 sec (max)
1150 psi	+160°F	0.30 sec (min)

(b) Maximum reel-in velocity not to exceed 12.0 ft/sec.

(c) Peak acceleration must not exceed 25 g and peak rate of onset of acceleration must not exceed 500 g/sec.

(d) The stall force shall be 100 pounds (±6 lbs.) per strap at 18 inches of extension at a minimum operating pressure of 850 psi. Under these conditions, the webbing straps shall not retract more than 0.25 inch.

(e) The force required to stall the inertia reel at the end of the retraction sequence and with pressure applied shall not exceed 50 pounds per strap at a minimum operating pressure of 850 psi.

General Dynamics - F-111 Crew Restraint System

The crew restraint harness is the G.Q. Parachute Co., Ltd., Part No. 480656 as designed by the British Institute of Aviation (see Figure 4, Ref 3). The powered inertia reel is mounted in the headrest housing and is attached to the upper torso restraint harness. Explosively powered retraction of the shoulder straps occurs upon ejection. The takeup time with the shoulder straps fully extended will not exceed 0.5 second.

The powered inertia reel was built for General Dynamics by Pacific Scientific Company to GD/Fort Worth Specification ZKO 3802, Revision F, Amendment No. 1, dated 20 December 1965. The Pacific Scientific designation is 0103157-35 Reel Assembly, Inertia Lock-Powered and 0103826-1 Gas Generator Assembly.

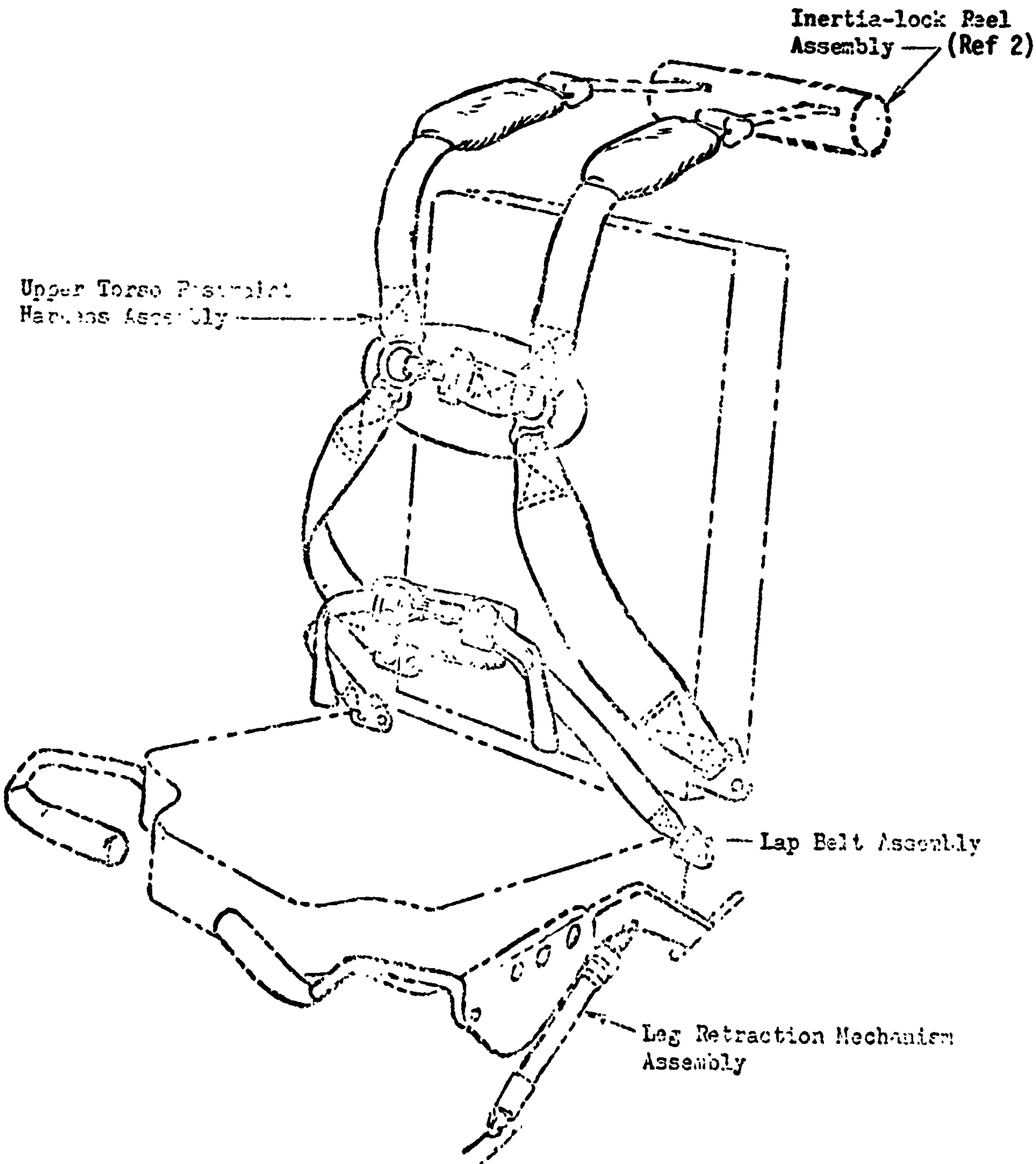


Figure 3. B-58 Restraint System

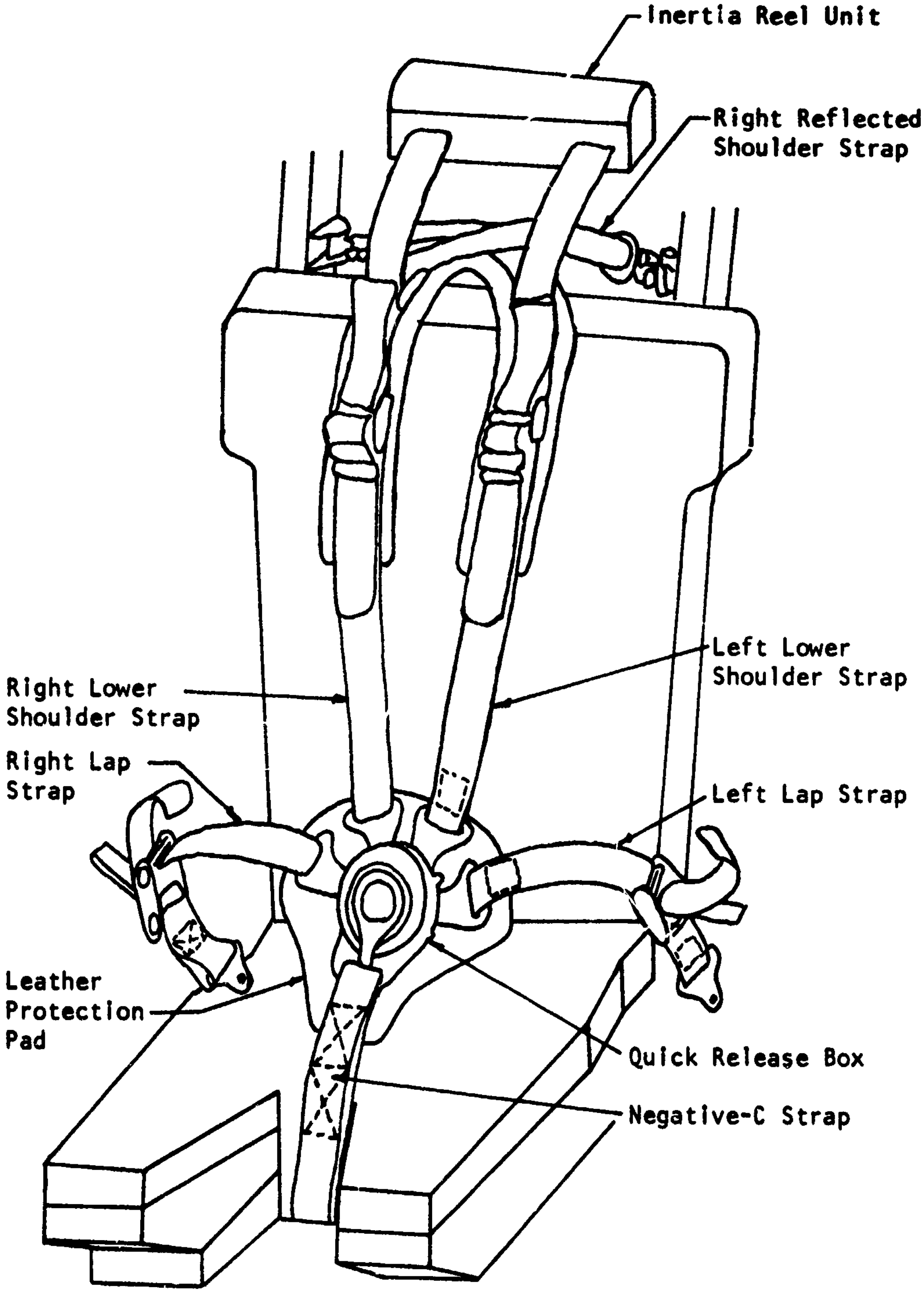


Figure 4. F-111 Seat with British I.A.M. Harness

The reel is built to accommodate a 5th through 95th percentile man as defined by WADC Report 52-321. It is equipped with a two position (automatic and manual) control handle which, when in the automatic position, initiates the lock mechanism when the acceleration on the crewmember is such that the shoulder strap reel out is at 3.0G. Initiation of ejection causes retraction of the shoulder straps regardless of the position of the control handle.

The specifications for this system are as follows:

(1) Distance - maximum of 18 incnes retraction.

(2) Time - maximum of 0.5 seconds for full retraction.

(3) Velocity - maximum of 12 ft/sec reel in velocity of the shoulder straps

(4) Acceleration - maximum of 25 g at center of gravity of the torso.

(5) Strap forces - during first second after initiation - maximum strap load of 450 pounds as described by a load spike with a base duration of 0.1 second. At 60 seconds after initiation - residual strap forces will be with a minimum single strap force of 15 pounds, a maximum total strap force of 140 pounds, a maximum single strap force of 84 pounds.

(6) Ignition delay - maximum of 10 milliseconds.

(7) Strap tension - the final strap tension, after ballistic retraction and unlocking of the reel, must not exceed the strap tension limits of 6.5 pounds maximum, 2 pounds minimum.

North American - A-5 Crew Escape System

The ballistic inertial reel (Rocket Power, Inc. P/N 1293-16) as shown in figure 5 (Ref 5), automatically positions and restrains the airman's upper torso. It is capable of positioning a 200 pound airman from the full out (18 inches) position under a 12 g load acting in any direction. The reel accelerates the airman with a peak acceleration of about 8 g with rates of onset of acceleration less than 500 g/sec. The peak velocity attained by the airman is about 9 ft/sec. North American claims that the forces imposed upon the airman during acceleration by the inertia reel are only 1/8 of the established human tolerance limits (Ref 6).

The upper torso bottoms out with the seat back through the personnel parachute and the head impacts the headrest. Anthropomorphic dummies were

Figure 5. A-5 Shoulder Retention

used to establish approximate head loadings. An accelerometer was mounted on the side of the dummy's helmet, and the dummy positioned at impact velocities up to 13 ft/sec. Peak acceleration was 53.3 g with rates of onset about 10,000 g/sec and a total acceleration duration of 0.020 sec. Six humans then impacted their heads in a similar manner until all had exceeded this acceleration pattern. The highest acceleration recorded was 67.3 g with a rate of onset of 13,400 g/sec and a total acceleration duration of 0.021 second. None of the subjects experienced any pain during or following the tests. There was no indication of a whiplash problem. It was concluded by North American that all forces imposed by the reel would be well within human tolerance limits.

Pacific Scientific Company, Ballistic Inertial Reel, PSCO-0103178-1

This specific powered ballistic inertia reel has been approved for use in USAF crew escape systems and is the one which Pacific Scientific intends to use as their standard for powered retraction applications.

The powered inertia lock reel, 0103178-1 (Ref 7), consists of three components: the reel portion, the power retraction device portion, and the gas generator. The reel, with only minor modifications, is an existing production unit qualified to specification MIL-R-8236. The gas generator is also a production unit that was qualified in conjunction with a similar inertia reel for the F-111 aircraft. This gas generator is qualified to specification MIL-D-21625.

Tests were performed to insure compatibility and satisfactory performance of the assembly under various conditions as required by the pertinent specifications. A production run of 25 units was produced. All parts were produced to production drawings with quality control on all phases of manufacturing and processing. Four units for the test program were selected at random from the lot of 25 units.

In summarizing the ballistic firing data, all Condition "a" (95 percentile with 100 pound opposing force) ballistic retractions were within specified limits and had an average time of 0.28 second for the 18-inch retractions. The average peak velocity was 8.4 feet per second. This includes firings at all temperature conditions.

All Condition "b" (5 percentile with no opposing force) ballistic retractions were within specified limits and had an average time of 0.23 second. The average peak velocity was 10.0 feet per second. This includes firings at all temperature conditions.

Following ballistic firing, and checking at one minute after retraction, the force remaining in the strap ranged from 75 to 120 pounds for all conditions of torso retraction.

The performance limits for load Conditions "a" and "b" were as follows:

Time - 0.3 second maximum for full retraction for temperatures of +200 and ambient; 0.4 second maximum for retractions at -65°F.

Velocity - 12 feet per second maximum reel-in velocity of the shoulder straps.

Acceleration - 25 g maximum at the center of gravity of the torso.

Strap forces - after full retraction from any position of extension, the shoulder harness strap force must not exceed 300 pounds in the first second, 200 pounds prior to manually unlocking the reel, and 140 pounds on the residual lock-up reading.

Ignition delay - 10 milliseconds maximum.

Talley Industries Powered Inertia Reels

Talley Industries has manufactured powered inertia reels for several aircraft including the XB-70 and the F-4. These systems subject the crewmen to essentially the same environment; however, the systems do differ in physical design. The B-70 system retracted a single strap 18 inches whereas the F-4 system used two straps 36 inches long in a doubled back configuration. In both systems the maximum haulback velocity was 10 ft/sec, and the maximum total strap force was 300 pounds for the first second and 150 pounds for the time after lockup. Both systems performed haulback within 0.3 seconds at room temperature and within 0.4 seconds at -65 F.

Universal Propulsion Company Powered Restraint Actuator
(Under License from Space Ordinance Systems)

Universal Propulsion Company manufactures a crew restraint-haul-back actuator that is of unique design. The device has been developed and tested by the manufacturer, but it has not yet been qualified for any aircraft installation. However, the manufacturer feels that his tests demonstrate that the unit is qualifiable.

The device uses hydraulics for inertia locking and for retraction, and it is of a linear construction rather than rotary. Power retraction is performed by a propellant device that drives a piston, which in turn develops the hydraulic pressure to retract the restraint harness. Test reports show that a complete retraction could be accomplished in less than 0.3 seconds with a peak velocity of 6.3 ft/sec.

The device also has unique inertia locking features in that it will lock on strap velocity, strap acceleration or aircraft acceleration in all three axes. In addition, the device reverts to the normal mode of

operation when the dynamics that caused the lock-up drop below a preset level. This differs from most designs and the requirements of military specifications because it does not remain in the locked position until the crewman cycles a release mechanism.

LEG RETRACTION AND RESTRAINT

Leg retraction is an area of the crew escape problem that is receiving a greater amount of attention. Injuries sustained during ejections resulting from flailing of the extremities and the inability in some cases of the crewmember to initiate ejection due to excessive g loads have emphasized the fact that this neglect cannot continue.

Applicable Military Specifications

The pertinent Air Force and Navy specifications covering ejection seats give only cursory attention to limb restraint. The paragraphs pertaining to leg restraint are reproduced below (arm restraint will be discussed later in this report).

MIL-S-9479A (USAF); 16 June 1967; Amended 27 November 1967
Paragraph 3.4.2.2.7

Seat Bucket Sides - To provide lateral leg retention, the seat bucket sides shall extend forward of the front edge of the ejection seat. The seat side extensions shall be designed to laterally brace the seat occupant's legs against the airloads encountered subsequent to ejection.

MIL-S-1847C(AS)(Navy); 1 April 1968
Paragraph 3.3.1

System Subsystem Design - The escape system shall include the following components/subsystems as applicable to the specific aircraft in which the system is utilized:

(a) (6) Torso, leg and arm positioning

Paragraph 3.3.1.1.1.3

Seat Sides - The ejection seat sides shall be designed to withstand maximum aircraft flight envelope dynamic pressure without failure during ejection. In addition, the seat sides shall provide space for the aircrewman restraint system emergency release handle on the starboard side. The seat sides shall also serve to contain the occupants thighs to prevent leg flailing during ejection. If the seat bucket sides protrude above the compressed sitting surface of the rigid seat survival kit, the seat bucket sides shall be flared outboard to accommodate the sitting hip breadth of the 98th percentile aircrewman wearing applicable flight clothing. A

minimum clearance of 20 inches shall be provided between the seat sides forward of the seat bucket as shown on BuWeps Dwg. 65A136H1.

Paragraph 3.3.1.1.6.2

Arm and Leg Restraint System - The ejection seat shall incorporate an arm and leg positioning and restraint system. This system shall automatically position and restrain the ejectee's arms and legs either as a pre-ejection function of the ejection sequence or immediately prior to limb exposure to windblast during ejection. As part of the leg positioning and restraint system the ejection seat sides shall be designed to prevent abduction of the legs when exposed to the maximum escape envelope dynamic pressure. Provision shall be made to ensure adequate clearance between the crewman's legs and feet and cockpit equipment and/or structure. The forces exerted upon the seat occupant to restrain his limbs shall not be injurious to him. An automatic limb restraint release shall be incorporated as a part of the harness release system. In addition, the limb retention system shall include a manual release which can be readily reached, grasped and actuated by a fully restrained seat occupant.

The USAF specification addresses itself only to providing lateral restraint in the form of a sideboard configuration. The USN specification meantions in a perfunctory and non-precise manner that the extremities shall be positioned and restrained during ejection. They, too, require the use of sideboards for lateral leg restraint.

Although the general specifications do not clearly spell out the need for and the performance of leg positioning devices, they have been included in a number of escape systems. The following is a brief description of these describing the retraction means and, if available, the performance specifications.

North American A-5 Crew Escape System

"Leg positioning and restraint are accomplished by lifting the knees and locking the feet in foot wells as shown in figure 6 (Ref 5). The knee-raising bar contacts the legs behind the knees. As the knees are lifted, the feet fall into foot wells, and the wells are closed by hooks. If the airman is experiencing acceleration loads, such that the feet will not fall into the foot wells, the hooks contact the lower legs and pull the feet into the wells. The system will operate under loads up to 12 g's." (See Ref 5).

"The pivot points of the knee-raising bar arms are below and aft of the pivot points of the hips. This ensures no submarining (forward movement of the lower torso) from the leg positioning action; should the airman's lower torso not be properly positioned due to improper harness adjustment, the leg positioning actually positions his lower torso."

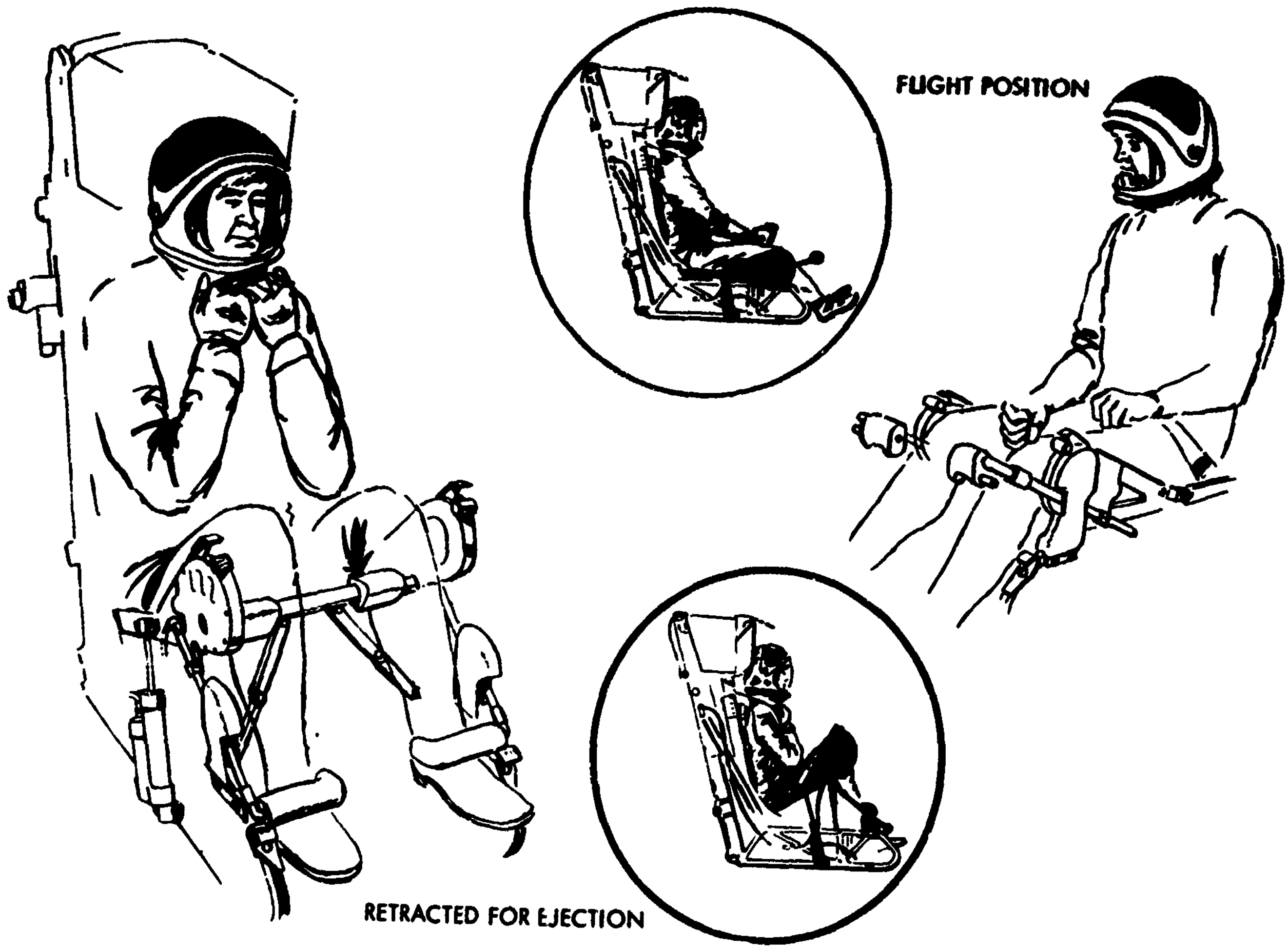


Figure 6. A-5 Leg Retention

"The forces imposed on the man by the leg positioning procedure are insignificant. The knee-raising bar has a maximum velocity of 5.3 ft/sec, and the heels have a maximum velocity of 9 ft/sec. All have energy absorption pads where they contact the legs. The system has been live demonstrated ten times, one of which occurred during an ejection during a flight emergency."

"The g's on the legs while attaining the velocity of the bar are quite low due to the attenuation afforded by the pads and by the muscle masses of the legs themselves. The restraining hooks seldom touch the legs, since lifting the knees swings the feet back into the wells. The hooks close the wells to prevent the legs from coming out in the windstream. (See Ref 6).

General Dynamics B-58 Escape Capsule

Leg positioning and restraint in the B-58 escape capsule, built for General Dynamics by Stanley Aviation Corporation, is accomplished much in the same manner as is done in the A-5 system, as can be seen in figure 7 (Ref 8). The two leg retraction thrusters are extended raising the thighs (by moving a leg lift bar upward beneath both legs and rotating the forward portion of the seat pan up) and stowing the feet back against the seat by rotating foot retraction bars downward. The information available on this system was primarily of a qualitative nature, the only performance specification given was that leg retraction would be accomplished in 0.6 second. Although no qualitative performance data was ever measured, the development of the system included tests with volunteer subjects. These tests demonstrated that the system operated within the range of human tolerance.

Lockheed C-2 Seat

Foot retraction on the C-2 seat system is accomplished by means of cables attached to the heels of the pilots boots. Attachment is made with a strap-on stirrup and coupling. The stirrup is so designed that a rapid lifting of the heel will disengage the boot from the stirrup.

The cable retraction is shown in figure 8. The ballistic actuator supplies power to the piston which in turn pivots the knee lateral support into position. Attached to the knee support is a cable which is wound onto one of two concentric reels of the reel mechanism. Attached to the other reel is the foot retraction cable. As the knee support mechanism is deployed the cable attached to it causes the reel to rotate which then causes retraction of the foot retraction cable.

Cushioning is provided for the retracting heel by means of a spring type shock absorber. As shown in the figure, the coupler (boot to cable) is tapered to permit its smooth entry into a socket on the ejection seat, which is spring loaded to act as an energy absorber. In addition, the retention of the coupler in the socket provides positive retention of the foot.

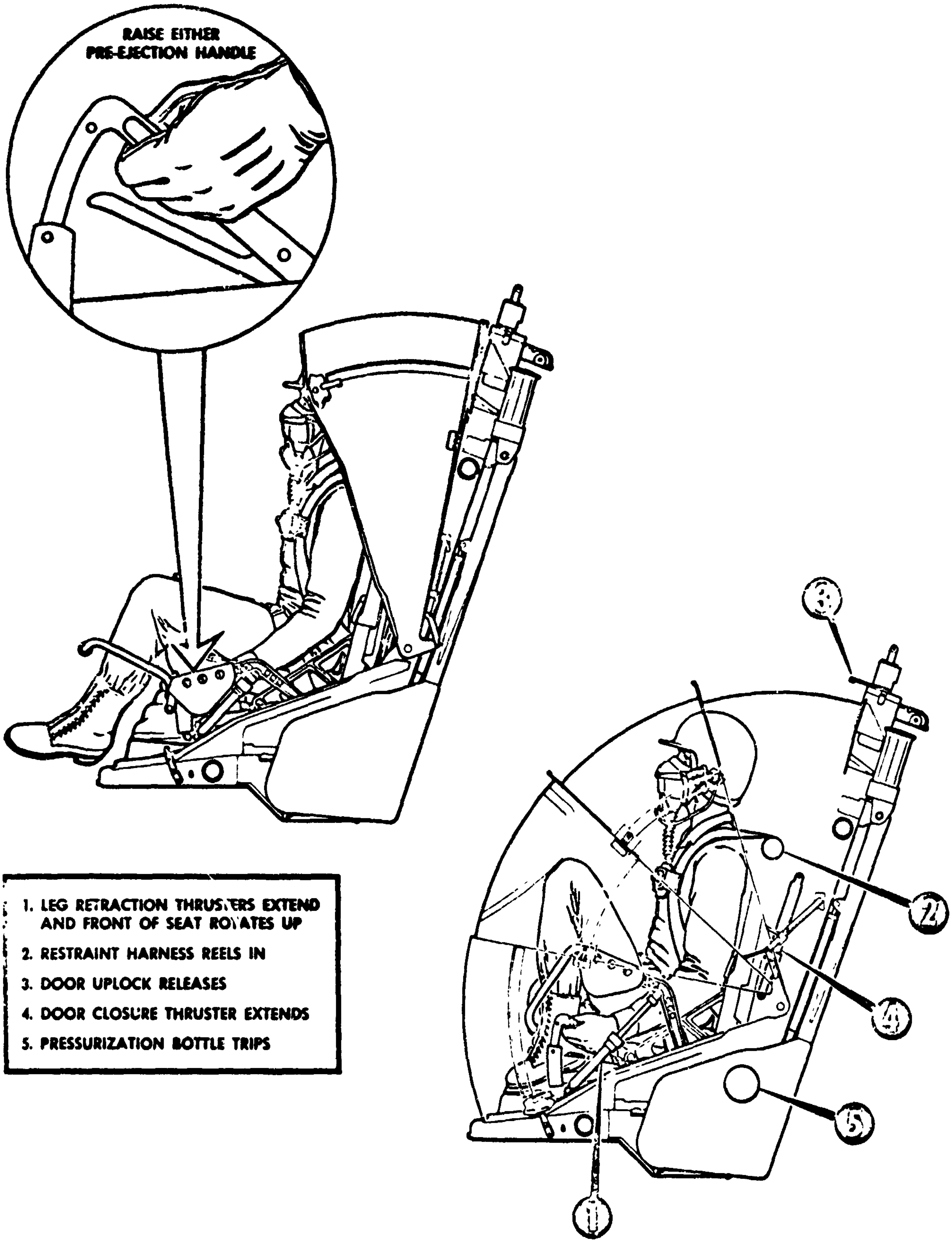


Figure 7. B-58 Leg Retraction

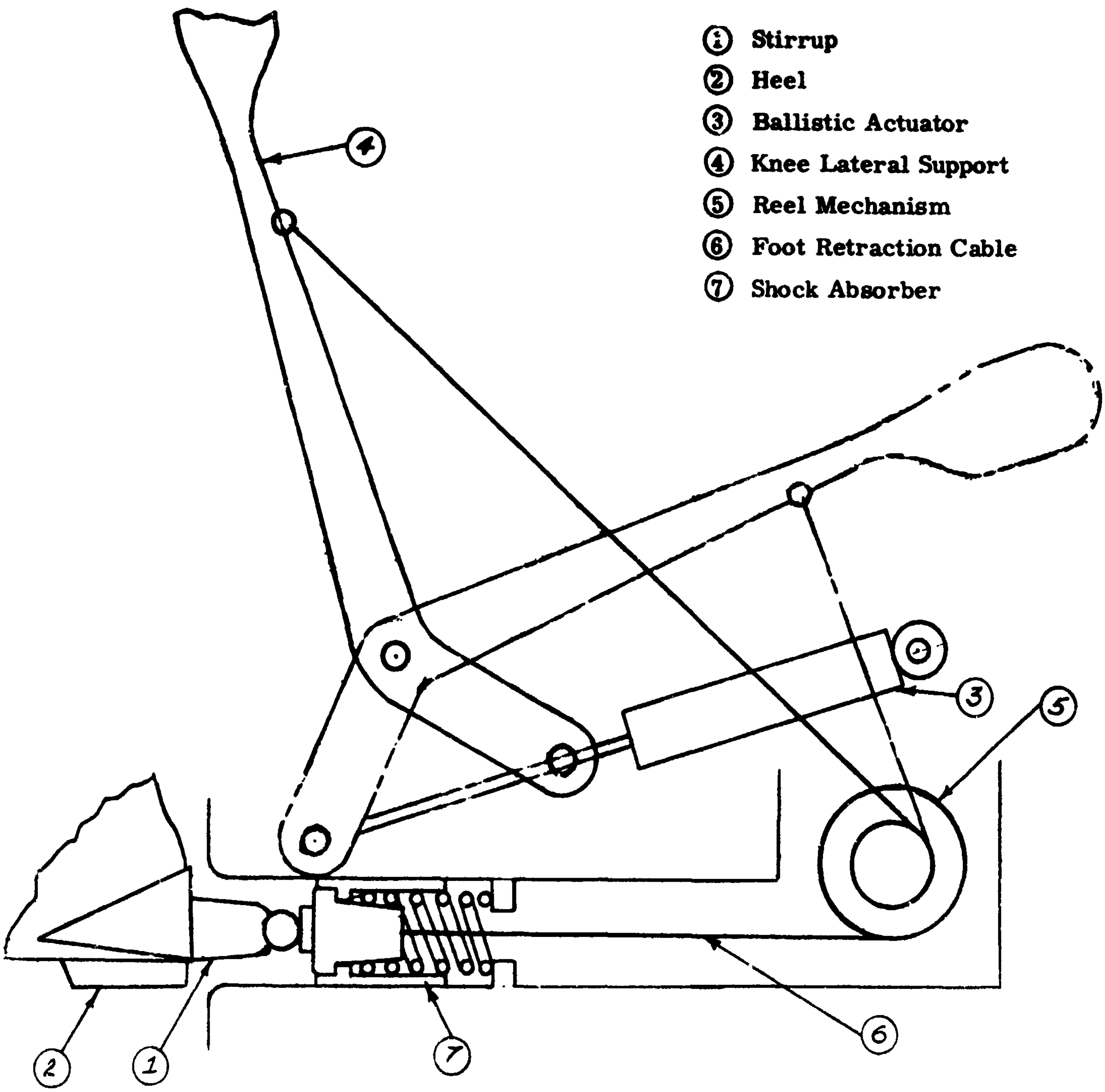


Figure 8. C-2 Seat - Foot Retraction

From a "Flight Test Data Report" for a 95 percentile human it was determined that retraction from the fully extended position (approximately 30 inches) was obtained in a minimum and a maximum of 0.36 and 0.43 seconds respectively. The cable tensions recorded during these tests range from a low of 304 to a high of 540 pounds.

The force required to extend the cables under normal use ranged from 0.5 to 4 pounds for the first 12 inches and from 1.0 to 4 for the remainder of the remainder of the extension.

North American XB-70 Escape Capsule

In the XB-70 an encapsulated seat is provided for emergency escape for each crewman. Recently this system was modified to include a leg retraction subsystem. Leg retraction is accomplished by powered retraction of a cable attached to the heel of the pilots boot. The system employs stirrups manually strapped to the occupants boots. These stirrups also include a quick disconnect fitting between each stirrup and the retraction cables. A schematic of the system is presented in figure 9.

Leg retraction is the final function performed during the pre-ejection sequence prior to the capsule doors closing. Retraction begins 0.8 second after sequence initiation and the capsule door closes at the 1.3 second mark, providing 0.5 second to complete leg retraction from a maximum distance of 30 inches.

However, the retraction motor must be capable of retracting an 80 pound mass that is restrained with a simulated inertia load of 400 pounds in less than 0.4 second and greater than 0.1 second. In addition, it must be capable of applying the retraction force through either only one cable or equally distributed through both cables.

North American X-15 Leg Retractor

The redesigned leg retractor in the X-15 escape system is also accomplished by powered retraction of a cable fastened to the heel of the pilots boot. This powered retraction represents a modification to the original system which required the pilot to kick aft causing ankle manacles to restrain the ankle. Other than the addition of power, the leg restraint mechanism remains as originally configured.

The pilot's boot is modified to include a heel plate with a stirrup which is fastened directly to the heel of the boot. The stirrup is attached to the cable which is coupled to the retractor mechanism. The foot is pulled into the foot pan and the heel strokes an actuator that positions the foot manacles (see figure 10) (Ref 10). At the end of the retraction the cables are cut and the foot is retained by the manacles

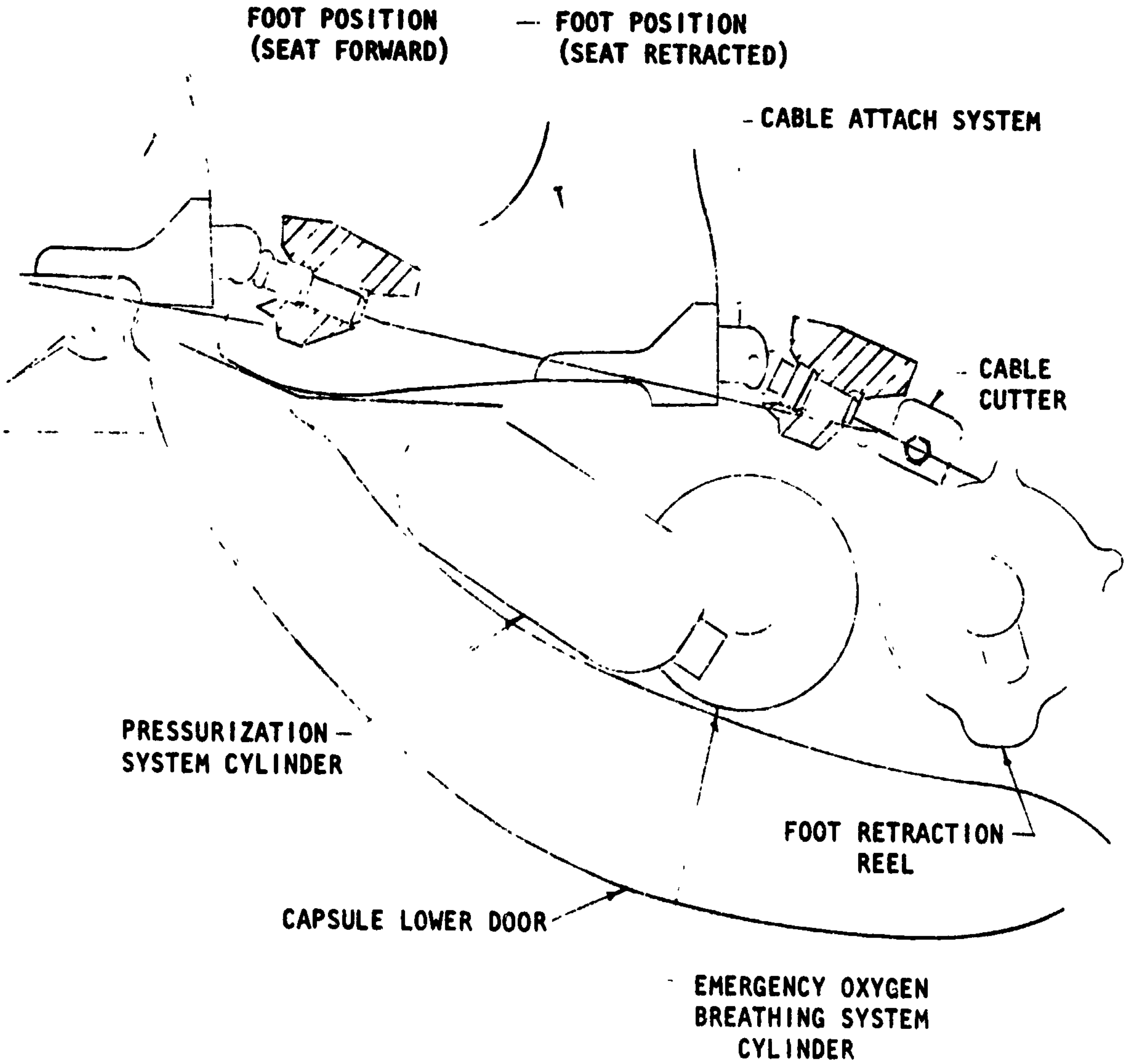


Figure 9. XB-70 Foot Retraction

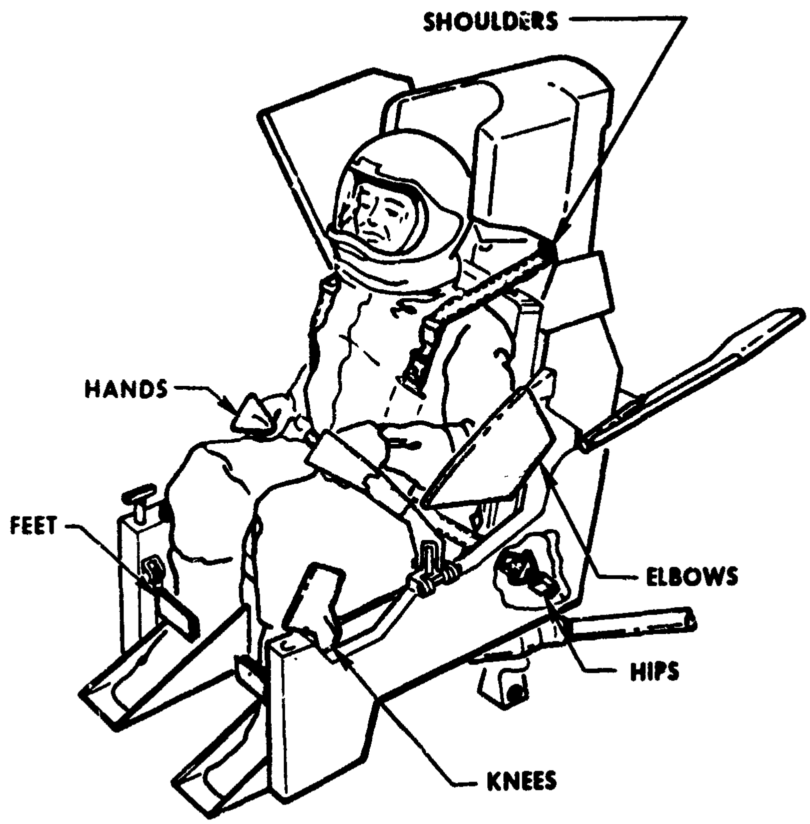


Figure 10. X-15 Restraint System

which lock to a closed position when the pilots feet are retracted full aft. Sideways motion of the pilots leg is prohibited by means of a knee brace which is displaced upward by motion of the ejection handles.

The powered foot retraction mechanism was tested by North American on human subjects both with and without a simulated inertial load on the leg. The inertial load was applied below the knee a distance equivalent to 1/4 the distance from the knee to the bottom of the foot. Loads as high as 155 pounds (representing 8 g) were applied during this testing.

The average maximum velocities obtained with the cables at their maximum extension of 22 inches (nominal extension is 18 inches) were 8 mph (11.9 ft/sec) with a 6 g simulation and 24 mph (35.2 ft/sec) without inertial simulation. The maximum tension in the retraction cable without simulated loading was in the neighborhood of 200 pounds.

The only impact energy absorption was obtained from the foot striking the manacle actuating mechanism and from the flexibility of the structure. The test subjects did not object to the foot impact, but the manacles, although rubber padded, were a source of discomfort.

Martin-Baker Leg Restraint

The Martin-Baker seat incorporates a leg restraint system that consists of a strap and garter that attach to the crewman's legs. The strap passes through a locking mechanism on the seat and then attaches to the aircraft floor with a shear pin. When the ejection seat moves up the rails the strap is pulled through the locking mechanism by the motion of the seat relative to the aircraft. When full retraction occurs a buckle on the garter bottoms out against the seat. This action shears the pin connecting the retraction strap to the aircraft and completes the retraction cycle.

The method of attaching to the crewman's legs differs from installation to installation. In most cases the garter is placed around the leg joint above the calf muscle. Other applications use two garters, one above and one below the calf muscle. In addition, in some installations the retraction straps are crossed behind the knees so that the legs are pulled together for further restraint.

There is some question as to whether or not the leg straps actually position the legs or merely restrain them. Some organizations feel that the legs are positioned inertially by the acceleration of the ejection seat. Others maintain that the straps actually pull the legs back and then restrain them.

Republic F-105 Leg Restraint

The F-105 escape system is being redesigned to include a leg restraint

system for the prevention of flailing injuries caused by windblast. The system is very similar to the Martin-Baker leg restraint in that it uses seat motion for retraction and it attaches to the leg with a garter at a location just above the calf muscle. In this installation the strap is attached on one end to the aircraft floor with a shear pin. The strap then feeds through the lock mechanism through the garter and then back up to the lap belt. The loose end is attached to the buckle of the lap belt and is released when the lap belt is released.

When the ejection seat moves up the rails, the strap is pulled through the locking mechanism and slips through the garter, and thus pulls the leg back against the seat. Upon reaching full retraction a buckle on the garter bottoms out on one of the strap guides and causes the shear pin to fail and release the strap from the aircraft floor. Release of the crewman is accomplished by releasing the lap belt buckle which in turn frees one end of the restraint strap. The strap is now free to slip through the garter when the legs are moved away from the seat.

ARM RETRACTION AND RESTRAINT

The area of arm retraction is one for which there is very little information available. To our knowledge there is but one system, that used in the North American A-5, which employs an arm retraction mechanism.

<u>Applicable Military Specifications</u>

The need of provisions for arm protection is evidenced in the pertinent Air Force and Navy specifications.

MIL-S-9497A (USAF)
Paragraph 3.4.2.2.8

Armrests - For comfort purposes, the ejection seat shall be equipped with armrests mounted on the seat bucket sides. The armrests shall provide lateral arm restraint, comfortably accommodate all crewmembers from the 5th to 95th percentile with their flight clothing, and shall not interfere with the crewmembers access to controls.

Paragraph 3.6.2.3

Armrest Structure - Each armrest shall withstand a down load of 200 pounds ultimate (135 pounds proof) distributed over an area extending 4 inches aft from the forward edge of the armrest and applied perpendicular to the armrest.

MIL-S-18471C (AS) (Navy)

The paragraph calling for arm and leg positioning and restraint is reproduced in the section of this report covering leg retraction.

North American A-5 Crew Escape System

As stated above the only system which is known to utilize powered arm positioning is the North American A-5 Crew Escape System. In this system, the arms are pulled up to the pilots chest by means of a ballistic cable reel. As can be seen in figure 11 (Ref. 5), a harness assembly attached to the pilots neck and shoulders provides the opposing force which causes the hands to be drawn up to the chest.

Straps are attached to each arm just above the wrist. These straps run up the medial side of the arms, through loops attached to the parachute risers, and into the center of the body where they are latched to a cable assembly. The cable passes down the front of the torso, through a receptacle assembly attached to the survival pack, around a pulley and into the ballistically powered cable reel. The system positions the airman's chest thus preventing injury from flailing following egress at high speeds.

The straps are pulled from the sleeve strap enclosures and through the loops as the reel takes up the cable. This brings the quick disconnect assemblies up to the loops, thus positioning the arms. The latch assembly bottoms in the receptacle at the same time the quick disconnect assemblies reach the loops. This locks the latch assembly in the receptacle and releases the cable from the latch assembly.

To enable the straps to be fastened to the wrists in a manner which would allow retraction while not encumbering or entangling the pilot, special sleeves must be worn. These sleeves provide for distributing the load over the wrists, a quick disconnect release knob and a Velcro fastened strap enclosure.

The sleeves are worn over the flight garment and attached together by one strap across the chest and two across the shoulders. The flight gloves are attached to the sleeves at the wrists to prevent the sleeves from sliding up the arms. The strap enclosures and the flight gloves could be attached to the flight garment (pressure suit or other flight suit), which would eliminate the need for the sleeves.

The arm retention system is normally disengaged during seat-man separation as the survival kit, attached to the airman, moves from the seat. This action releases the retention straps from the latch assembly. The airman can also release his arms at any time through the quick disconnect assemblies at the wrists.

The final velocity of the arm straps is about 30 ft/sec. Velocity of the straps at the time they start accelerating the arms will vary from about 8 ft/sec to 30 ft/sec, depending upon the position of the arms when the escape sequence is initiated.

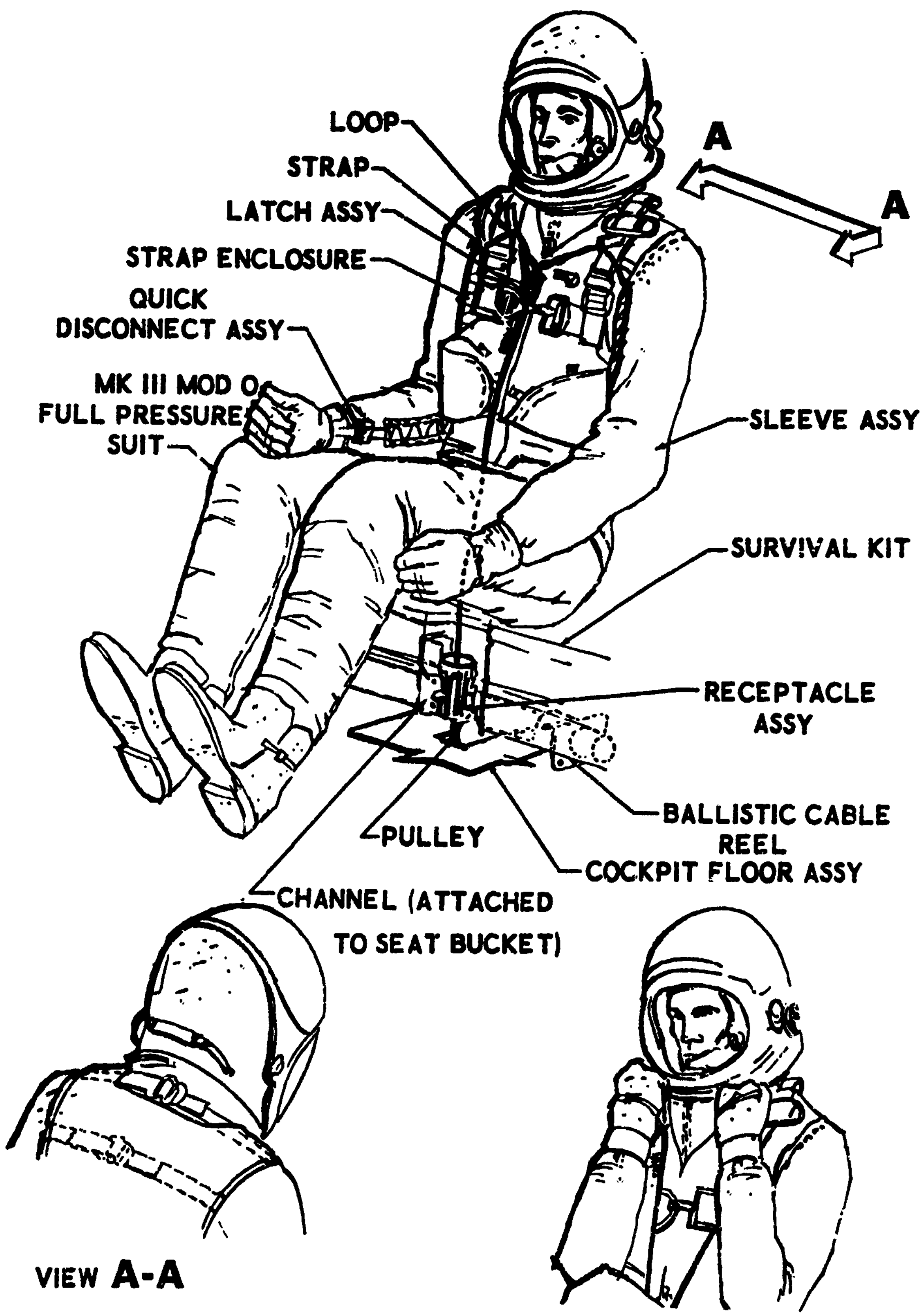


Figure 11. A-5 Arm Retention

Live tests were conducted to determine the maximum allowable cable velocity, using subjective reactions as endpoints. Since the pilot can eject the navigator without any warning, these tests were conducted with the arms placed in every conceivable position within the cockpit. Cable velocities were reasonably constant from the time of load application on the arms to the bottoming of the latch in the receptacle assembly. These tests were discontinued when the cable velocity reached 62 ft/sec, even though the test subjects believed their tolerance limit to be much higher. The ballistic cable reel produces peak cable velocities of less than 35 ft/sec. It has been live demonstrated seven times using production cable reels and numerous times using a pneumatic system as a power source.

Arm Restraint Systems

While the incidence of arm retraction is rare, the provision for arm restraint is somewhat more common. The majority of the system affect arm restraint by having the pilot clutch the D-ring, ejection handles or face curtain with armrests sometimes being utilized for lateral support. However, there are a few systems which utilize more elaborate restraints. A brief description of two of these follows:

Lockheed C-2 Seat

The C-2 seat employs a webbing type arm restraint. The webbing is pulled into position by the leg guard as it rotates into position (reference figure 8). This webbing then acts as a barrier that prevents the arms from being carried beyond the seat envelope.

North American X-15 Escape System

Arm restraint is obtained when the pilot initiates ejection by squeezing both ejection control release levers and rotating them upward and in-board, the end position being the pilot's lap (see figure 10). This motion simultaneously causes the armrests to rotate inboard from their normal position, laterally restricting the elbows.

AUTOMATIC PELVIC RESTRAINT

Presently there are no operational escape systems that incorporate automatic pelvic retraction or restraint. There have been several concepts proposed by various organizations; however, none of these have reached production. Stencel Aircraft has used a ballistic inertia reel as a lap belt tightener and the Frankford Arsenal (Ref 11) has developed a ballistic lap belt tightener that is a part of the lap belt mounting hardware. In this design the fitting that attaches the lap belt to the seat contains a ballistically actuated piston and cylinder (see figure 12) that is normally in the fully extended position. When the device is actuated the piston is driven into the cylinder thereby shortening the total length of the cylinder and end fitting. In an actual installation the lap belt would have one of these devices attached

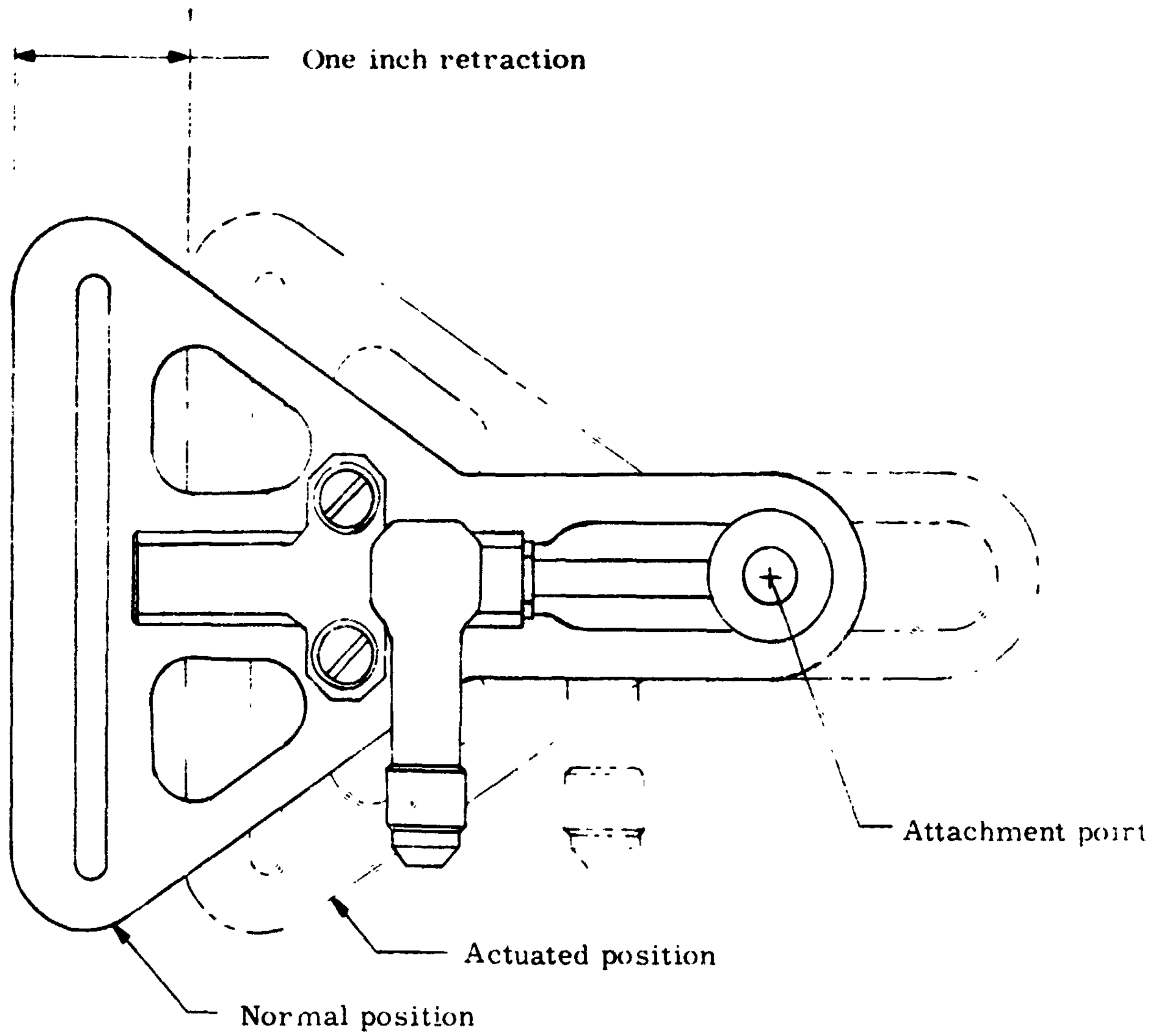


Figure 12. Frankford Arsenal Lap Belt Tightener

to each end. Each actuator is capable of shortening one inch which would effect a total lap belt shortening of two inches. The piston in the tightener could retract with a 400 pound force and then could react against a 600 pound force without slipping. Each lap belt tightener is capable of carrying a maximum force of 4000 pounds.

Some of the other concepts that have been proposed, but not developed, will be presented in a later section of the report, but will not be presented here because they are not existing systems.

SECTION IV

DESIGN CRITERIA

The parametric study, Section II, presented a list of parameters pertinent to escape system automatic body positioning and restraint subsystems. This section of the report addresses itself to those parameters that were defined as Design Criteria. The discussion in the following paragraphs is presented to establish some bounds on the quantitative values to be placed on these parameters.

BODY SEGMENT RETRACTION DISTANCE

The retraction distances required are dictated by the dimensions contained within MIL-S-9479A, Seat System: Upward Ejection, Aircraft, General Specification for; and AFSCM 80-1, Handbook of Instructions for Aircraft Design.

Leg Retraction Distance

Drawing AD1 from AFSCM 80-1 presents the basic dimensions for stick controlled aircraft. It was assumed the leg retraction system would be attached 1.25 inches from the bottom of the foot and 4 inches from the heel. These dimensions were applied to the appropriate rudder pedal dimensions, assuming the maximum pedal width of 10.5 inches. The retracted position is then 4 inches forward of the seat pan forward edge, and 4.5 inches from the aircraft centerline. These are in tabular form (see Figure 13):

	X	Y	Z
Forward	44.500	10.250	4.000
Aft	19.375	4.500	1.250

The dimensions are relative to the intersection of the neutral seat reference point in the forward (X) direction, the heel rest line in the vertical (Z) direction, and the aircraft centerline in the lateral (Y) direction.

The total distance from the forward to stowed position is 25.9 inches. This amount of cable or strap would be necessary to draw the foot from the extended outboard position into a position against the seat pan. It is not possible to extend the leg further since the 44.5 inches is the distance from neutral seat reference point to neutral rudder position and then includes maximum rudder travel and adjustment. If both legs are extended equally to the maximum pedal adjustment, the total distance of retraction is reduced to 22.7 inches. The extreme value could exist if the pilot were

All Dimensions from AFSCM80-1 Drawing AD1

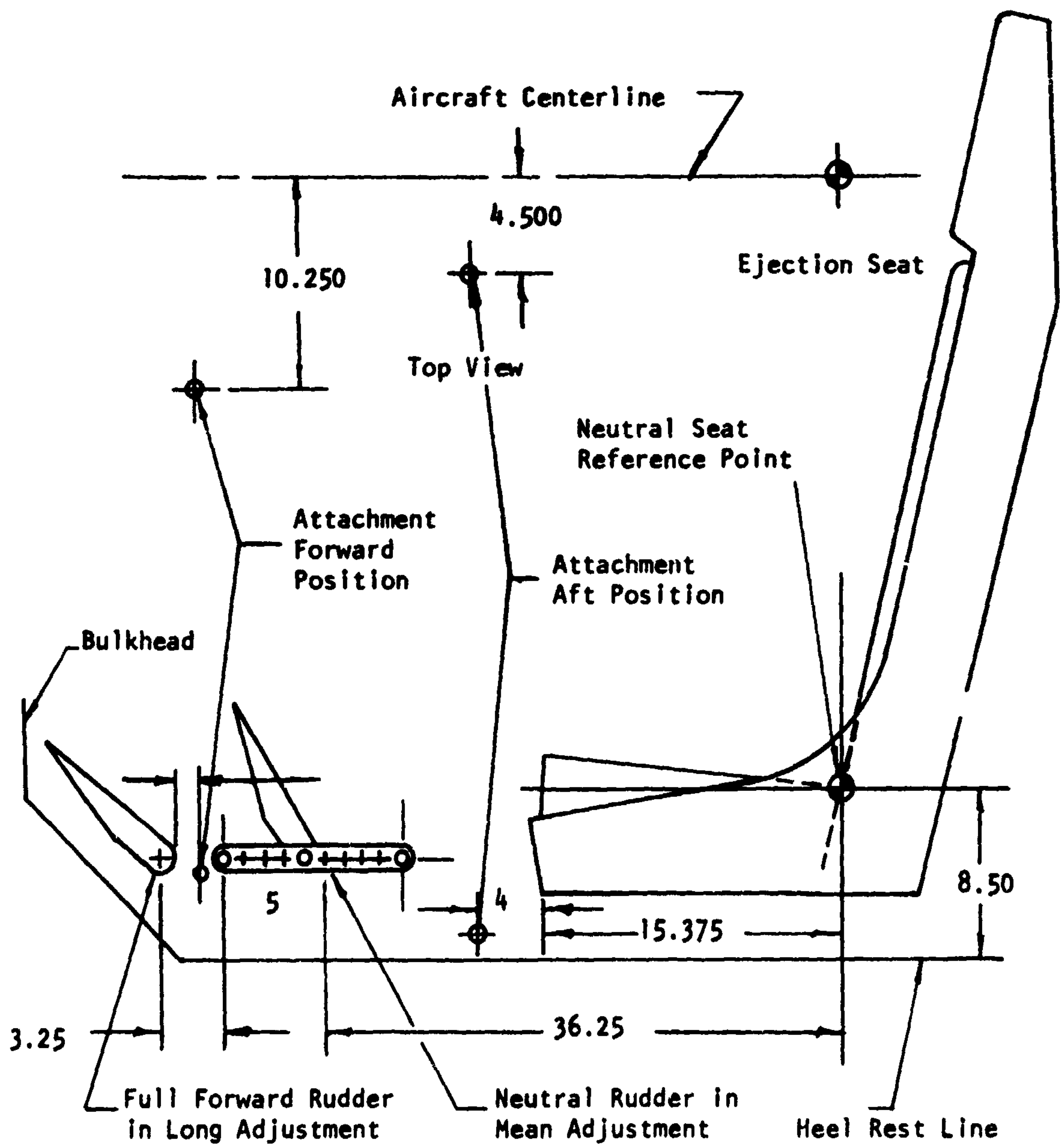


Figure 13. Leg Retraction Distance Schematic

attempting to counteract adverse yaw during ejection. The maximum could be a reasonable estimate of a condition necessitating ejection.

Arm Retraction Distance

The arm retraction distance was determined by assuming that the arm is extended diagonally across the top of the knee and then retracted to a position on the chest. The dimension used to locate an attachment point was the functional reach as defined by Hertzburg (Ref. 12). As shown in figure 14 a line was drawn from the shoulder pivot and across the knee cap. In the top view this places the arm beneath the throttle reference point. The tabulated dimensions are:

	X	Y	Z
Forward	26.500	15.375	16.000
Aft	4.000	3.000	39.000

These are also relative to the aircraft centerline, heel rest line and neutral seat reference point.

The total displacement required is 33.4 inches. If it is assumed that the hand were on the throttle, this would be reduced to approximately 28.3 inches.

It is quite possible that arm retraction could be implemented by retracting the elbow and drawing the arm segments into place. If this is done the elbow dimensions for the extended and retracted positions are:

	X	Y	Z
Forward	10.500	11.000	26.000
Aft	0.750	8.000	18.375

The total displacement for the elbow is 12.7 inches in going from the extend position to one along the spinal axis and against the rib cage.

Pelvis Retraction Distance

The pelvis is retracted by drawing an integral or external strap into the seat back and seat pan intersection. If this is to be done by a strap, it is required by MIL-S-9479A that the lap belt be drawn through attachment points located on an angle of $45^{o} \pm 2^{o}$ with respect to the seat bucket bottom. The distance of retraction must be selected by considering the freedom of movement usually desired by a pilot. If the smallest pilot has his knee against the instrument panel as shown in Figure AD2 of the

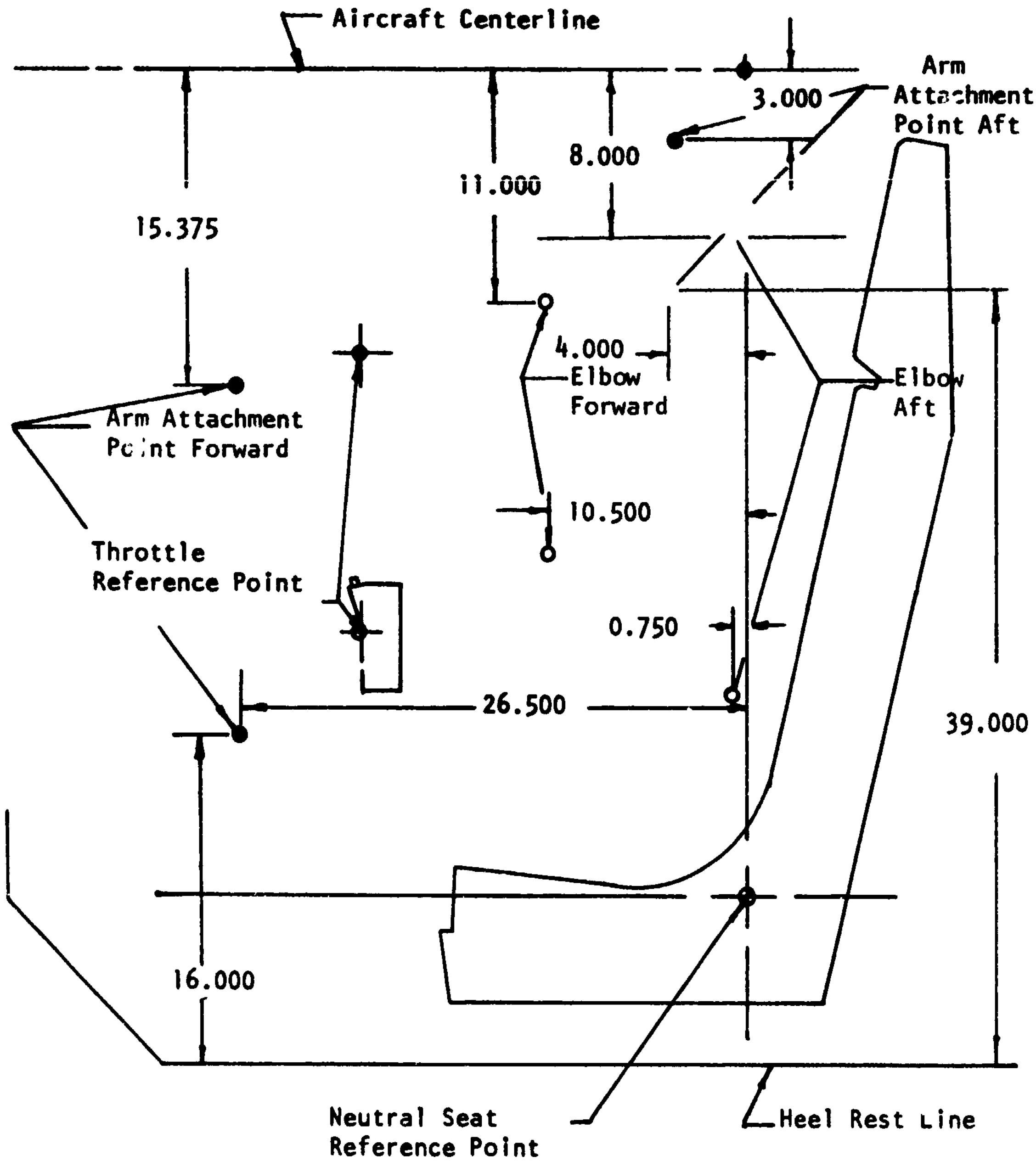


Figure 14. Arm Retraction Distance Schematic

mentioned specification, the hip pivot point must travel approximately 13 inches to return the pelvis to a seated position. This number is obviously a remote possibility. A realistic number would be to consider the distance the pelvis separates from the seat during an "eye balls out" deceleration. In the absence of such data, it seems reasonable to assume that the pelvic area could not compress more than one-half waist depth. This implies a retraction distance of 4.75 inches for the 95th percentile man.

Shoulder and Head Retraction

The upper torso restraint is required to be capable of positioning the seat occupant through 18 inches of travel according to MIL-S-9479A. If this dimension is used with the hip joint as a pivot point, the upper torso can swing into the locus of stick reference point movement and the chest to a point nearly over the stick neutral point. The head clearance line becomes tangent to the instrument panel. This implies that for the larger man the 18 inch dimension permits the maximum travel permitted by cockpit clearances. If an attachment were placed at the head center of gravity, the travel is approximately 19 inches.

For design purposes the 18 and 19 inch travels are indicative of the maximum restraint distances. However, the restraint of the head should obviously be relative to that of the shoulders since the relative motion between the two segments is more critical than the absolute motion of each.

EJECTION SEAT VOLUME ENVELOPE

The maximum volume contained by man and restraint hardware is limited by two envelopes. The ejection seat as shown in MIL-S-9479A establishes the basic dimensions that the back, buttocks and head must conform to. Additional restrictions are established by virtue of the limits of seat adjustment from the heel rest line. These are shown on the figures of the specification more clearly than can be described and dictate an internal volume that cannot be violated. An external volume is established by the cockpit clearance dimensions drawing of AFSCM 80-1. The described volume is a 30 inch by 30 inch area parallel to the ejection path, perpendicular to the plane of the seat back and passing between the instrument panel and neutral seat reference point.

Examination of the sitting dimensions of a 95th percentile man points out that the clearance dimensions specified require the feet to be in a stowed position. That is, although it is desirable to have a volume available between operational or functional limits and the restrained position, the existing requirements may not permit such a volume to exist. It may possibly be advantageous to have a cushion material between the ankles and seat pan. The volume of cushion material can force the legs into the cockpit clearance area, but it must compress sufficiently and quickly enough that it would permit the legs to be within the clearance limits during the travel up the rails. The established clearance limits are shown in figures 15 and 16.

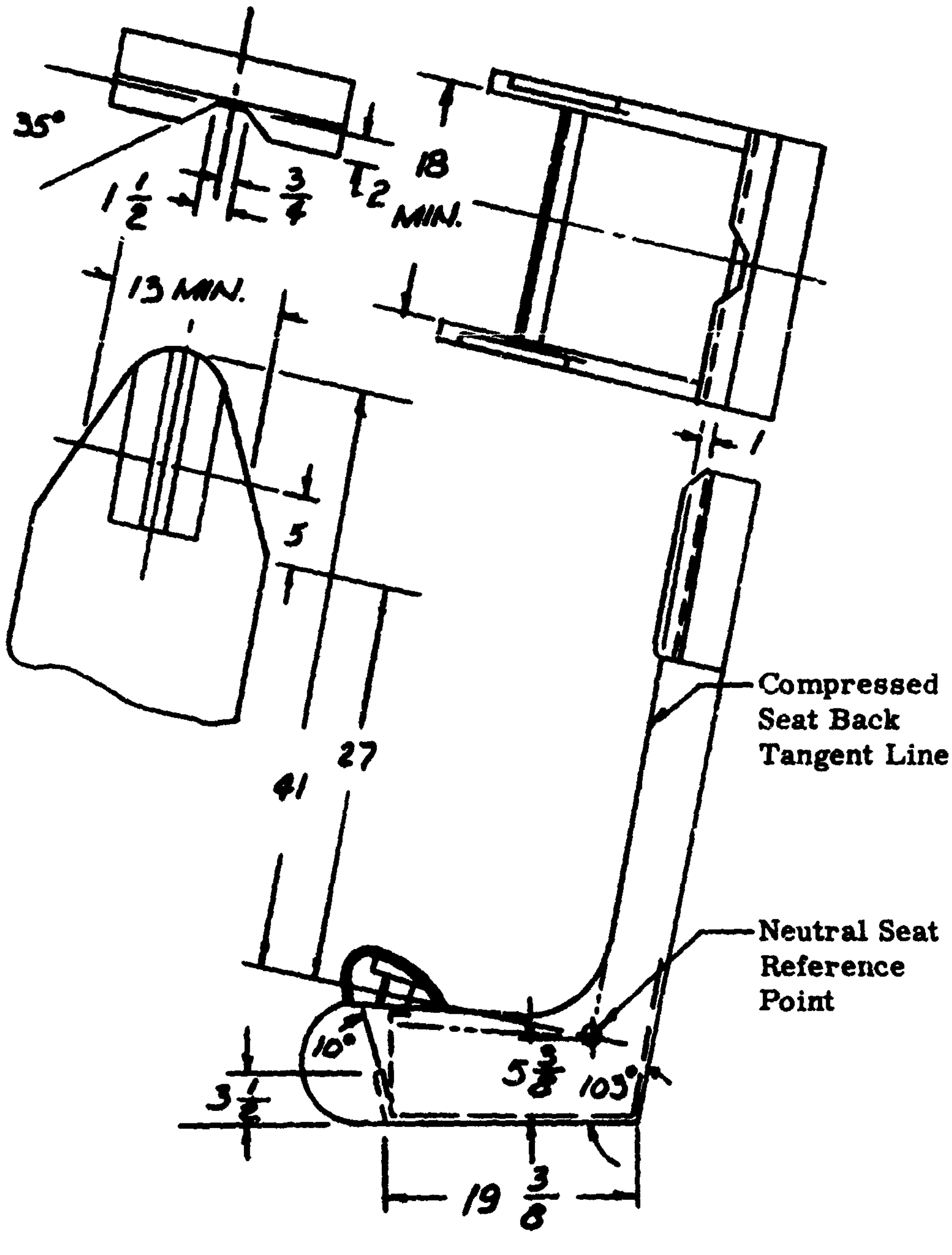


Figure 15. Ejection Seat Limits

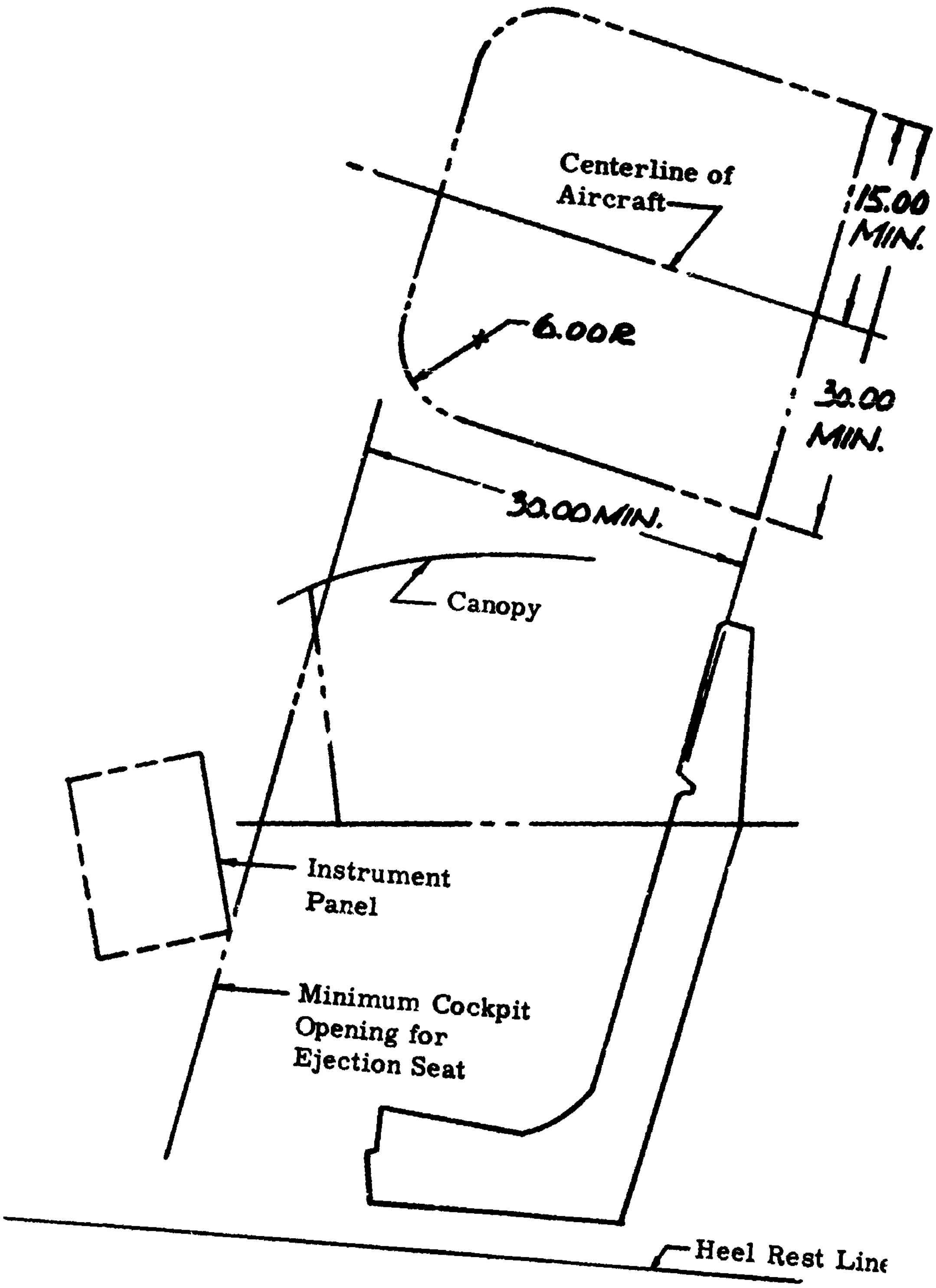


Figure 16. Cockpit Clearance Limits

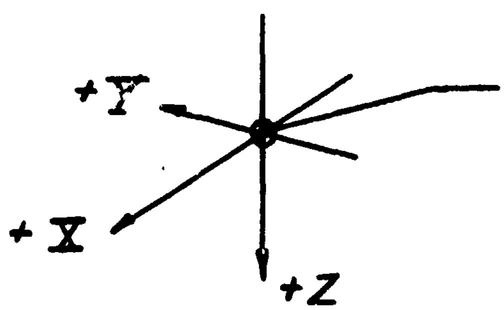
AIRCRAFT ACCELERATION ENVIRONMENT

The restrain hardware and associated retraction components must be able to function under and withstand two different acceleration environments. The maneuvering accelerations during flight will create inertial forces that the retraction devices must be able to overcome. Accelerations during a crash must not cause loads that will exceed the ultimate strength of any component.

It is not possible or practical to analytically or statistically describe the exact nature of expected crash and maneuver accelerations. There are many crash test reports and flight loads reports that present a variety of acceleration waveforms for many types of aircraft. Because of this variety the best estimate of these environments for design purposes is that presented in the applicable military specifications. The following discussions contain the acceleration environments currently used.

Crash Accelerations

Crash acceleration data has been collected from three sources. There are significant differences in the data in that magnitudes differ, some acceleration directions are not specified in other specifications, and the time dependence as shown by a waveform is only referred to in one document. Some of the accelerations have been calculated from force requirements that assumed a 215 pound man. In those instances, the force limit is also presented. The acceleration limits are considered to act separately except for the one specification, MIL-S-18471C, Ref. , which requires all to act simultaneously. The acceleration magnitudes and directions are shown below with the acceleration time duration plots:

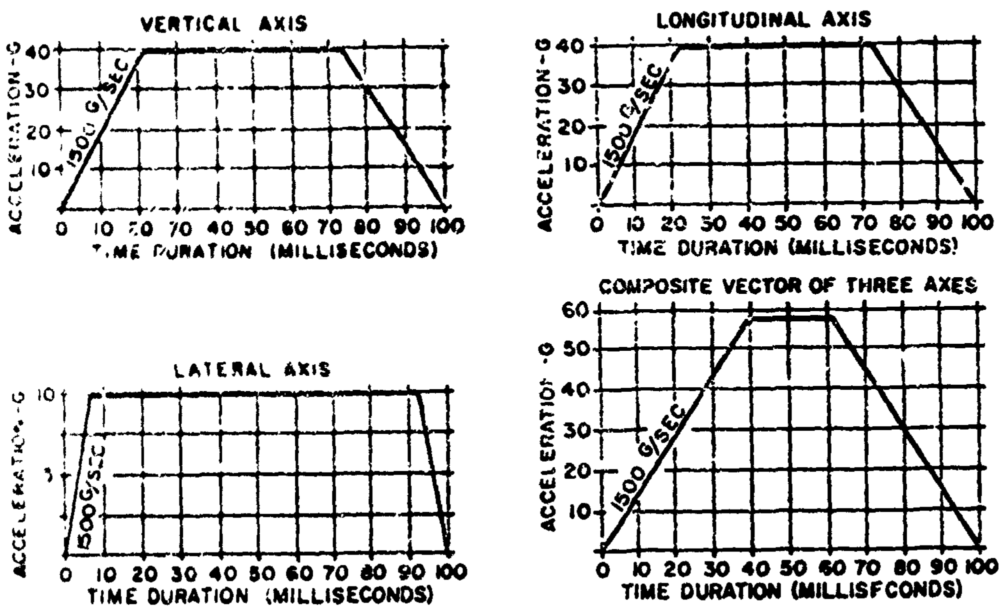


Center of gravity of man-seat combination for Navy specifications and USAF seat structures. Center of gravity of occupant only for USAF restraint hardware.

	X	Y	Z	Resultant
MIL-S-18471C Seat System (Navy)	+40G	±10G	+40G	+58G
MIL-A-8865 (a) Aircraft Strength (Navy and USAF)	+40G +20G	±13.70G ± 6.85G	+20G +10G	None
MIL-S-9479A Seat System (USAF)	+40G -6.97G (1500#)	±13.70G	+20G (4300#) -8.15G (1750#)	None

(a) Upper row is for all land based except VR, VP, VW, VS, VU, bomber, transport and cargo aircraft. Lateral accelerations are calculated based upon an azimuth angle of 20 degrees from the longitudinal axis.

Impact Acceleration - Time Exposure

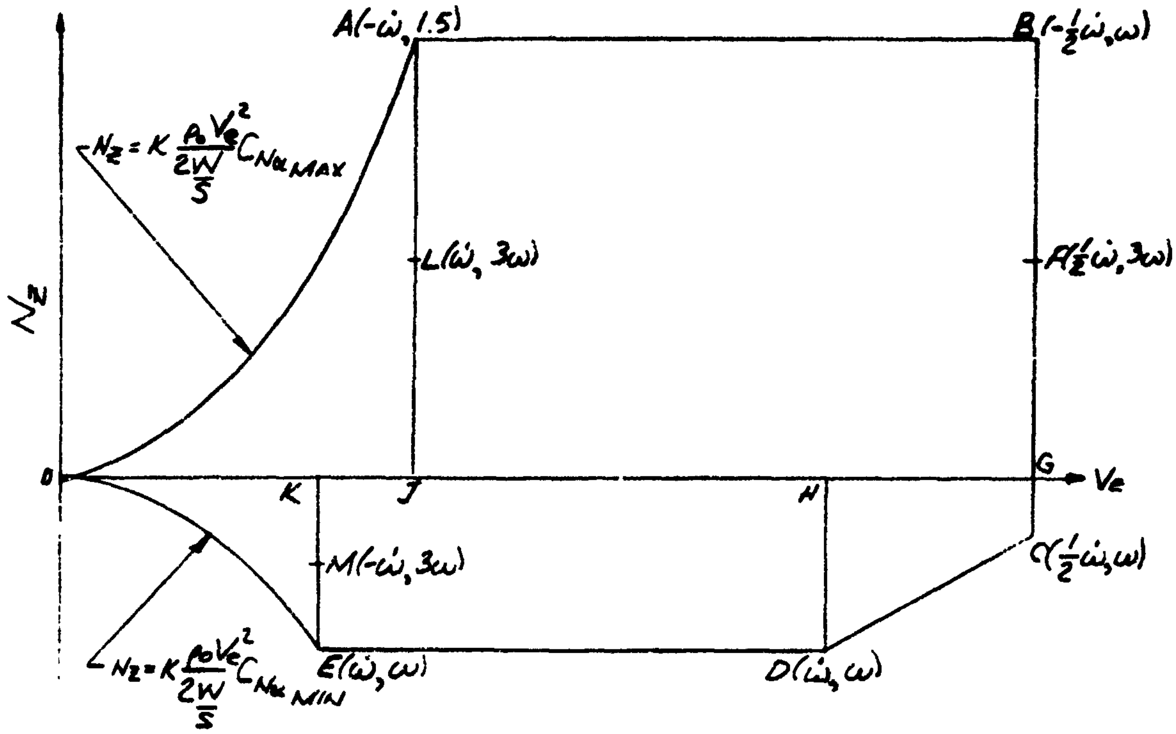


These plots are only applicable to the acceleration of MIL-S-18471C.

Maneuvering Accelerations

As the aircraft maneuvers in going from one attitude to another the cockpit is subjected to accelerations that are functions of the translational and rotational motions of the center of gravity of the aircraft. These can be quite complex motions and there are, therefore, digital programs currently used to calculate the accelerations at a point on a vehicle. Despite the obvious difficulty of having an infinite number of possible acceleration-time profiles, there are maximum values that can be determined based upon specified values of translational and rotational motions. These are tabulated in MIL-S-8861 and are applicable to all Naval and Air Force aircraft. Figure 17 is taken from this specification and is the V-n diagram for symmetrical flight.

Figure 17. V-n Diagram for Symmetrical Flight



NOTES:

1. JA = GB = value specified in column 3 and column 6, Table I.

2. GC = value specified in column 5, Table I.

3. HD = KE = value specified in volumn 4 and column 7, Table I.

4. OH = V_H.

5. OG = value specified in column 8, Table I.

6. JL = GF = 0.5 JA.

7. KM = 0.5 KE

8. k = 1.25 for $M \leq 0.4$.

   = 1.0 for $M \geq 0.6$.

   = 1.75 - 1.25M for $0.4 < M < 0.6$.

   where M is the Mach number corresponding to the speed being considered.

9. Where a value of pitching acceleration other than zero is specified,

the magnitude of the pitching acceleration at each point is specified by the first quantity in the parentheses, where $\dot{\omega}$ = value specified in column 9, Table I.

10. The magnitude of the pitching velocity in radians per second at each point is specified by the second quantity in parentheses, where $\omega = gn/v$.

11. At altitudes at which $OJ \geq OH$, the pitching velocities and accelerations at points A and L shall be those specified for points B and F, respectively.

The V-n diagram describes the velocity and acceleration envelope that the aircraft must operate within. Since the diagram is for a symmetrical maneuver, the cockpit acceleration environment is only a function of the center of gravity vertical acceleration n_z, and the pitching rotation, ω. The notes below the figure indicate how each of the values are found from the table of Figure 18. The only value not so specified is $OH = V_H$, which is the level flight maximum speed attained at basic flight design gross weight in the basic configuration with maximum thrust available.

For any type vehicle the cockpit acceleration is found by calculating the angular effects and adding their components to the translational. As an example, the vertical acceleration at the cockpit is:

$$a_z = n_z + x\dot{\omega} - z\omega^2$$

where x is the horizontal distance from aircraft center of gravity to the cockpit, and z is the vertical.

The acceleration is the normal acceleration n_z, the acceleration due to an angular acceleration $x\dot{\omega}$, and the centripetal acceleration $z\omega^2$.

There are other specifications that relate to the development of maneuver loads due to control displacements and unsymmetrical flight conditions. The acceleration environments for these conditions can only be calculated knowing all of the stability derivatives, the inertial characteristics, and the power and attitude conditions that existed prior to the maneuver. This cannot be easily calculated even when the physical properties are known and therefore unless it is known that a particular maneuver is critical for the cockpit, the symmetrical data must be used.

PRE-POSITIONING TIME

The time available for positioning the crewman prior to ejection is an extremely difficult parameter to quantify. Immediately one has the tendency to state that the minimum time possible is the optimum. However, in view of the total escape sequence this may be over-specified and unnecessary.

In the case of open ejection seats the crewman must be pre-positioned prior to ejection into the airstream. Normally pre-positioning is accomplished

Class		Symmetrical Flight Limit Load Factor					Limit Speed V_L	Pitching Accel. $\dot{\omega}$ rad/sec^2,	Time for Abrupt Elevator Control Displacement t_1, sec
		Basic Flight Design Gross Weight		All Gross Wts.	Max. Design Gross Weight				
Air Force	Navy	Max.	Min. at V_H	Min. at V_L	Max.	Min. at V_H			
1	2	3	4	5	6	7	8	9	10
F_I		8.67	-3.00	-1.00	4.00	-2.00	As specified in Specification MIL-A-8860 and as otherwise approved by the Procuring activity	6.0	0.2
$F_{II}TF$	VF, VA, VT	7.33	-3.00	-1.00	4.00	-2.00		6.0	0.2
	VO	6.00	-3.00	0	3.00	-1.00		5.0	0.3
T		5.67	-2.33	0	2.00	-1.00		5.0	0.2
L	VU	4.00	-2.00	0	2.50	-1.00		3.0	0.3
B_I		3.67	-1.67	0	2.00	-1.00		3.0	0.3
B_{II},		3.00	-1.00	0	2.00	-1.00		2.0	0.4
$C_{Assault}$	VP, VW, VS, VR	3.00	-1.00	0	2.50	0		2.0	0.4
$C_{Transport}$		2.50	0	0	2.00	0		2.0	0.4
B_{III}		2.00	0	0	2.00	0		2.0	0.4

Figure 18. Symmetrical Flight Parameters

within the time required to eject the canopy, but if the frangible canopy now under development is used the canopy will be penetrated by the first motion of the seat and pre-positioning must occur more rapidly. The time is also reduced in crew escape modules since the entire cockpit can be ejected immediately upon ejection initiation. It is possible that pre-positioning does not have to be complete before catapult firing. It may be feasible for both open ejection seat and crew escape module to have prepositioning occur, at least some portion, during the initial motion of the escape system.

According to Navy personnel the removal of the canopy is the limiting factor for crewmen pre-positioning, because canopy removal may require as long as 0.8 seconds under adverse conditions. However, with good conditions the canopy may be jettisoned within 0.1 to 0.2 seconds. Therefore, the first motion of an ejection seat could occur within 0.2 seconds if the escape path is clear. Similarly, Air Force personnel indicated that an average time of 0.5 seconds was required for ejection seats to clear the aircraft. This time includes an average of 0.25 seconds for the seat to move up the rails. Frequency time data of this nature was not available for crew modules escape systems at the time of this study.

With the objective of reducing the pre-positioning sequence to 0.2 seconds in mind, consider the case of shoulder retraction. Assume a crewman has to be positioned through a distance of 18 inches within the 0.2 seconds. To accomplish this it is necessary to retract the man at a velocity of 7.5 ft/sec, which is well within the limits of both the Navy (9 ft/sec max) and the Air Force (12 ft/sec max) specifications. This calculation assumes a square wave input and, of course, propellant actuated devices of the type currently used cannot deliver a square wave velocity input to the man nor can conventional restraint materials transmit them; however, this example is presented to place some bounds on the minimum pre-positioning time.

A crew escape module requires a different analysis. Again assume that retraction of the shoulders is over 18 inches but must be accomplished in less time since there is less time available. For example, if the positioning is accomplished in 0.1 seconds, the velocity is 15 ft/sec which is still less than measured data with human subjects.

The above discussion was presented to illustrate that the optimum time for the pre-positioning sequence, at least in the case of open ejection seats, is not necessarily the minimum time required. Indeed this could lead into a hurry up and wait problem, where the crewman is violently pre-positioned but then must wait until some other event has occurred before the ejection sequence continues. As systems develop however, it appears that the difference between "minimum" time and time available may be rapidly diminishing. (After the time period of this investigation it was found that operational data of the F-111 capsule indicate that the time required from sequence initiation to peak thrust will be less than 0.1 seconds.) Therefore, it appears that the time required for prepositioning can only be

established after the entire escape sequence for the particular system has been thoroughly analyzed. Viewing the current state-of-the-art it appears that prepositioning within 0.1 to 0.2 seconds will be required to cover the spectrum of systems available.

ACTUATOR PERFORMANCE VARIABILITY

The variability of actuator performance is one of the larger problems encountered in the development of body positioning and restraint subsystems. Normally these actuators use pyrotechnic devices as energy power sources. The pyrotechnic device is desirable because it is lightweight and it is capable of delivering a large amount of energy in a short time. Unfortunately, these devices are quite sensitive to the environment and mechanical loading and therefore have variable performance capabilities.

Recent tests by Mr. Stan Coryell of Grumman Aircraft Engineering Corporation have demonstrated the performance variability encountered with powered inertia reels. One device tested required 0.245 seconds for full retraction at ambient temperature. However, at -65F the same device required 0.405 seconds for full retraction. This is a variance of 0.16 seconds from the ambient temperature operating time of 0.245 seconds. Thus we see that the variance in operating time can be of the same order of magnitude as the normal operating time. Similarly, another device tested with a human subject showed considerable performance variation under different loading conditions. Under ambient conditions and with and without a 2 g acceleration environment the device completed a 16-1/2 inch retraction in 0.31 seconds and 0.17 seconds respectively. Thus the retraction time variation, 0.14 seconds, is again of the same order of magnitude as the normal retraction time.

The Air Force and Navy specifications for powered torso retraction devices list a maximum operation time of 0.4 seconds (-65F). The minimum time computed from velocity and retraction distance specifications is in the range of 0.165 seconds. Therefore a total time variability of 0.235 seconds is permitted by these specifications.

A discussion with ballistic actuator designers seems to indicate that the above discussion reflects the state-of-the-art. Thus, it appears that the variability of a ballistic device designed to operate with 0.3 to 0.4 seconds will be in the range of 0.1 to 0.2 seconds. (Later data relative to the F-111 capsule indicate that there may have been significant improvement in these figures. The capsule has ballistic components which must have variability in the range of 0.01 to 0.02 seconds in order to operate within 0.10 second to peak thrust.)

DESIGN CRITERIA DISCUSSION AND CONCLUSIONS

The research effort reported in this section was generated from the result of two previous tasks. The first task involved the development of the

relationship between the parameters that are important to the design of automatic body positioning and restraint subsystems. The relationship presented graphically as a parametric flow diagram, demonstrates how one design parameter influences the parameters. It also illustrates that the man, seat, and the aircraft all blend into one system and that none of these items can be treated as a separate entity.

The second task involved a study of existing retraction and retention subsystems. This study revealed that systems for retracting the upper torso and the legs have received the most attention. There is one operational system that retracts the arms and there are virtually no operational systems that pre-position the head or the pelvis. There are conclusions that can be drawn about each of these subsystems.

Torso Retraction

A review of the performance capability of existing powered inertia reels and the pre-positioning sequence time seems to indicate that maximum velocities of 9 ft/sec and 12 ft/sec, specified in the military specifications, are more than adequate. In addition these retraction rates have been safely demonstrated by numerous human tests. If a nominal velocity of 9 ft/sec is used, an 18 inch torso retraction can be accomplished in 0.165 seconds. This is much less than the average time that is elapsed between ejection sequence initiation and ejection seat movement. However, torso retraction with existing systems can require from 0.3 to 0.4 seconds. Therefore it appears that if any changes are required it should be in the operating characteristics of the powered inertia reels rather than increasing the maximum retraction velocity. Reducing the performance variability of the devices would appear to be the most significant improvement.

Leg Retraction

Retraction and retention of the legs has had considerable activity since the design of the B-58 and the A-5. The designs incorporated in the B-58 and the A-5 seem to be the most advantageous from the standpoint of encumbrance; however, there is also a weight penalty involved with these systems. The spur type leg retractors used in the Lockheed C-2 seat, the X-15, and the XB-70 offer positive retraction and retention of the leg and foot. These devices are capable of rapidly retracting the leg and they effectively distribute the accelerating forces over the area of the flight boot. Unfortunately the cables used in these devices are objectionable from the encumbrance standpoint. The garter leg restraint device used in the Martin-Baker seats and the F-105 restrain the knees and the upper portion of the lower leg but do not offer effective restraint to the lower leg. These devices also have the encumbrance problem caused by the use of straps.

North American has retracted the leg through 22 inches in 0.08 seconds under laboratory conditions simulating the XB-70 system.

Therefore it appears that retraction of the legs can be accomplished within the same time period required to retract the upper torso.

Arm Restraint

Only the A-5 ejection seat incorporates an arm retraction subsystem. This device seems to be quite acceptable from the standpoint of encumbrance and weight. North American has conducted some arm retraction tests simulating the A-5 system. In these tests cables attached to the wrist were retracted through the shoulder harness at a location in the center of the chest. In these tests, cable retraction velocities up to 62 ft/sec were obtained. Even at this velocity the subjects believed that their tolerance limit was much higher. Therefore, this data seems to indicate that arm pre-positioning can be easily accomplished within the time available for pre-positioning.

Head and Pelvic Retraction

The study of existing systems revealed that there are very few developments in the area of head and pelvis retraction. In addition, there has been very little experimentation in these areas. Therefore if retraction of either the head or the pelvis is to be seriously considered it will first be necessary to conduct experimental studies to establish design criteria and performance limits.

The above data were used in quantifying of the parameters defined as design criteria in the parametric study. These parameters were retraction distance, ejection system volume envelope, aircraft acceleration environment, pre-ejection time and actuator performance time. The definition of the first four parameters was performed by correlating the data from military specifications and technical reports. The data on the last two parameters was gathered from test reports and from conversations with engineers active in the field. The conclusion that can be derived from these data is that pre-positioning for ejection seats does not have to occur in less than 0.2 seconds where the aircraft canopy is conventionally removed and that 0.3 seconds is probably a more realistic design time. For crew escape modules it is more realistic to reduce these values to 0.1 and 0.2 seconds. In addition, it was discovered that there were no data available on pre-positioning sequencing except that all retraction devices in the A-5 seat are actuated simultaneously. Therefore it appears that an investigation of the optimum sequence for retracting should be conducted.

SECTION V

DEVELOPMENT OF NEW PRINCIPLES AND TECHNIQUES

One of the major objectives of this study was to develop new concepts for automatically positioning and restraining the body segments of a crewman. In order to accomplish this it is first necessary to examine the purpose and function of these systems.

The primary function of these subsystems is to position a body segment prior to ejection or capsule separation. After the segment has been positioned it is necessary to restrain it and thus protect it from windblast injuries or impact with the surrounding structure in the case of encapsulated seats or crew escape modules. Review of this general requirement shows that there is a limited number of ways in which this can be performed. First, the force used to position the body segment has to be a pushing force, a pulling force, an inertial force, or one that rigidizes the subject. Secondly, the force can be applied by means of a permanently attached element, by grasping the body segment, by hooking the body segment, or by moving body support structures. Using these general classifications in a table such as that presented below, any concept can be grouped into one of the categories represented by the squares in this figure.

	Method of Applying the Positioning Force			
Type of Force Applied	Permanent Attachment	Holding or Containing	Hooking or Grasping	Motion of Structures or Supports
Push				
Pull				
Inertia Loading				
Rigidization				

If every concept can be placed into one of these squares, it should be possible to systematically select conceptual designs by considering each of these squares and the techniques suggested. For example, the top left hand square covers retraction techniques in which the actuator is directly attached to the body segment and retraction is accomplished by a pushing force. The designer can now consider techniques where a body segment is pushed into place by an element that is attached to the crewman or his personal gear. This process can be repeated for each of the categories represented in the above figure.

This approach was used to develop a nucleus of conceptual ideas. The results are presented in Table I and require further explanation. Some of the squares in Table I were eliminated because the functions indicated by the two coordinates do not develop logically or are redundant. For example, inertia loading by means of holding or containing is contradictory since the former implies a dynamic condition and the latter implies a static condition. The reasons for eliminating each crossed-out block are presented in Table II.

At this point Table II was reviewed for conceptual categories that seemed to possess the most potential. The criteria for this selection were practicability, encumbrance, effectiveness and weight. Based on an evaluation using these criteria two concept categories were selected. The first was the category of techniques that uses a pull force through a permanently attached element and the second was the category that uses a pull force with a hooking or grappling element. In addition, these categories were further restricted to exclude all rigid elements or mechanisms. This final restriction was based on a consideration of weight effectiveness. It is known that the most efficient structure available to man is a flexible tension member. The reasons for this are that these unidirectional members are self-aligning and stable. Conversely, rigid elements that transmit eccentric loads carry weight penalties because they must be designed to prevent bending and buckling failures.

An example would be the comparison of the Lockheed C-2 seat (F-104) and the North American HS-1 seat (A-5 aircraft). Both of these seats include a system that retracts and restrains the foot. The C-2 seat uses a technique in which a cable is attached to the flight boot with a stirrup. When actuated the cable is retracted and a fitting on the stirrup couples with a receptable on the ejection seat for positive retention. The system is of lightweight construction because it requires only the stirrups, high strength cables, holding receptable and the drive motor. However, the system has the obvious fault of encumbrance caused by the cables attached to the crewman's feet.

The HS-1 seat uses a more complex system that does not have the encumbrance disadvantage; however, its construction is much heavier. In this case, a ballistic actuator first lifts the crewman's knees. When this occurs the inertia loading causes the feet to swing back into foot wells. Simultaneously the foot wells are closed by a hook mechanism that restrains the feet. This system is obviously much heavier than the cable system because it requires a large mechanism for lifting the knees, rigid elements for hooking the feet and deep rigid foot wells. In addition, the actuator must be larger because of the increased mass of the mechanism.

Considering this example and the selected concept categories discussed above, it seems that the optimum solution is to develop a system tnat has the combined advantages of the C-2 and HS-1 seats. That is, a system that causes little encumbrance and is lightweight.

Table I. System Concept Categories

Type of Force \ Method of Force Application	Permanent Attachment	Holding or Containing	Hooking or Grasping	Motion of Structures or Attachments
Push	(1)	(2) Inflatable bags; clamping devices (devices that squeeze sideways on body segments).	(3)	(4) Clam shells; rotating seat pan to push up legs; moving foot wells; devices attached to the aircraft and that push the crewman into the seat.
Pull	(5) Attached cables and straps; rigid attachments; exoskeleton concepts; artificial muscle; flexible webs attached to the flight suit; extendable scissors-type devices; bladders or linkages that shorten when inflated.	(6) Nets	(7) A-5 leg retraction; B-58 leg retraction; snares; retractable bars; retractable bungee cords.	(8)
Inertia loading	(9)	(10)	(11)	(12) Lifting of the knees in the A-5 and the B-58 systems; inertially positioning one body segment by moving another.
Rigidization	(13) Locking flexible columns; devices that rigidize when pressurized; quick freezing of fluid; elements in garment; exoskeleton;	(14) Cocooning techniques; X-15 foot manacles.	(15)	(16)

Table II

Concept Category		Reason for Elimination
(1)	Push and permanent attachment	A pushing device would have to react against the aircraft structure. This, together with permanent attachment, implies that the crewman is coupled to the aircraft. Such a concept is inherently undesirable.
(3)	Push and hooking or grappling	The concept of attaching by hooking or grappling implies that a pull force would be applied to the subject. Thus, grappling or hooking is contradictory to a push force technique.
(8)	Pull on motion of structure or attachments	This combination is redundant in that concepts falling in this category could also be classified in concept category (7).
(9)	Inertia loading and permanent attachment	The advantage of inertia loading is that motion can be imparted to one portion of the body by moving another portion and thus eliminating the need for direct attachment of any type. Therefore the two methods are contradictory.
(10)	Inertia loading and holding or containing	Same as (9).
(11)	Inertia loading and hooking and grappling	Same as (9).
(15)	Rigidization and hooking or grappling	The concept of rigidization implies that something on or about the crewman rapidly rigidizes to effect body positioning or restraint. The concept of grappling or hooking implies that a mechanism reaches out, finds the crewman and attaches to him. Using these two definitions, the concepts do not seem compatible.
(16)	Rigidization and motion of structures or attachments	The same reasoning in (15) applies.

CONCEPTS USING FLEXIBLE ELEMENT, PULLING TECHNIQUES

It is extremely difficult to conceive unique ideas in this relatively well studied design area. However, there are several ideas that appear to be worth discussing. These are shown specifically for retraction for the legs, but the concepts may be applicable to other body segments.

The first is an extension of the cable and foot stirrup concept. Figure 19 indicates that the cable is attached to the foot or ankle but that the cable is contained within a tear-out section of the flight suit. Within the suit is a ring attachment point that can be snapped onto a retraction cable that is integral to the seat. During actuation the retraction cable pulls downward on the ring tearing the integral cable from the leg of the suit. The cable from ankle to ring is extracted from the suit and the foot follows straight back into the seat.

This concept does not have the encumbrance problem of the stirrup configuration and yet does have the original advantages of lightweight, stable retraction. The disadvantages are the possibilities of not attaching the ring, and that of severe retraction motion if the tear-out is not a continuous pull.

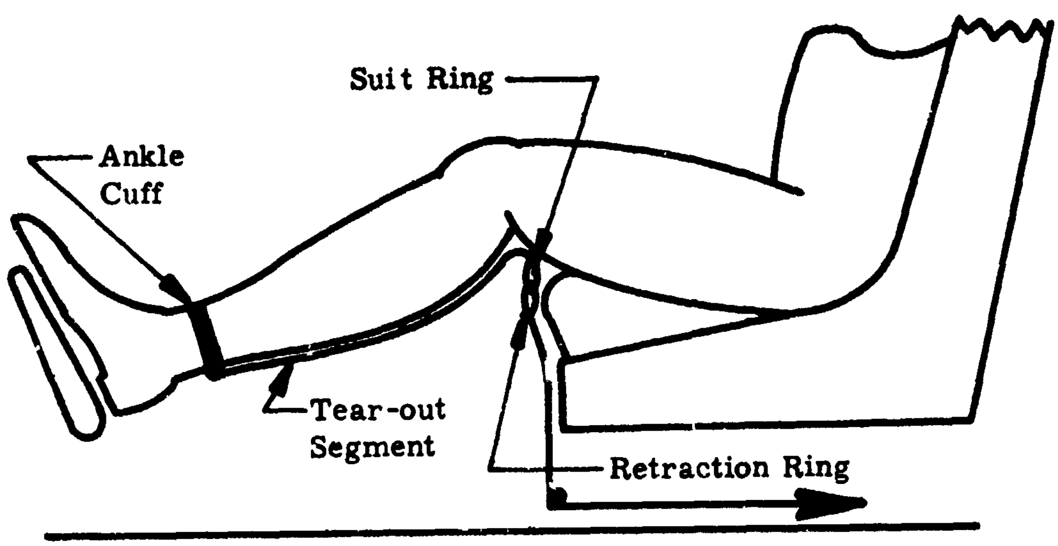


Figure 19: Tear-out Cable Device

Another idea is shown in figure 20. The objective of this technique is to have the restraint cable contained within the cockpit structure in tear-out material. The loop is outside of the leg movement envelope and above the foot. It could be contained within the instrument structure and

returning along the aircraft centerline taking advantage of the existing control stick envelope requirement. There is obviously no encumbrance and the strap again has the advantage of being able to snare the limb regardless of where it is located. There is the potential hazard that the velocity attained by the strap prior to contacting the leg could be sufficient to cause injury. The padding, surface area and elasticity of the strap could be adjusted to any optimum configuration.

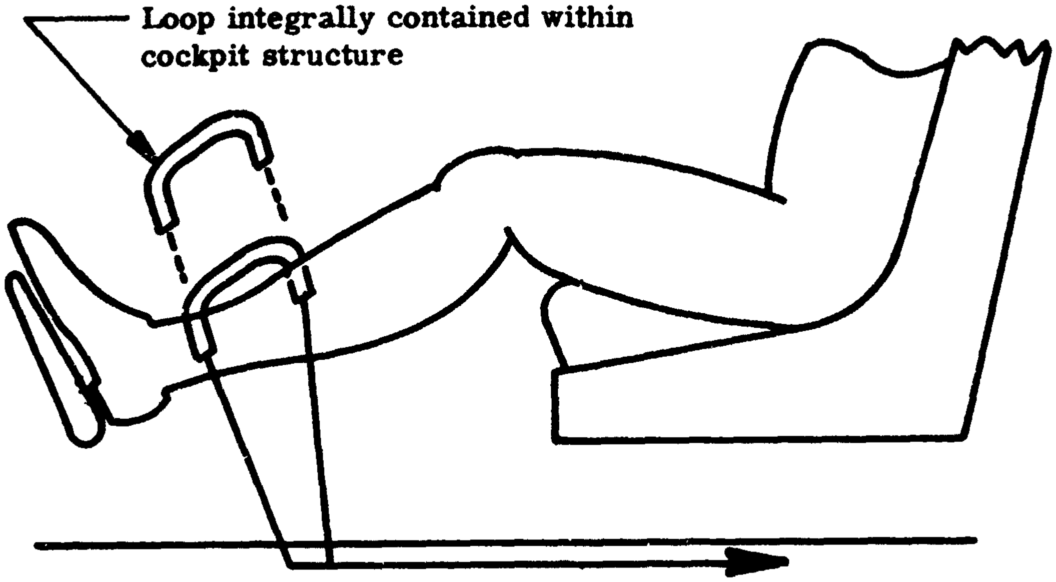


Figure 20: Snare Adaptation Device

Another similar concept is that of figure 21. This is very similar to the previous in that the snare is still present. However, it is assumed

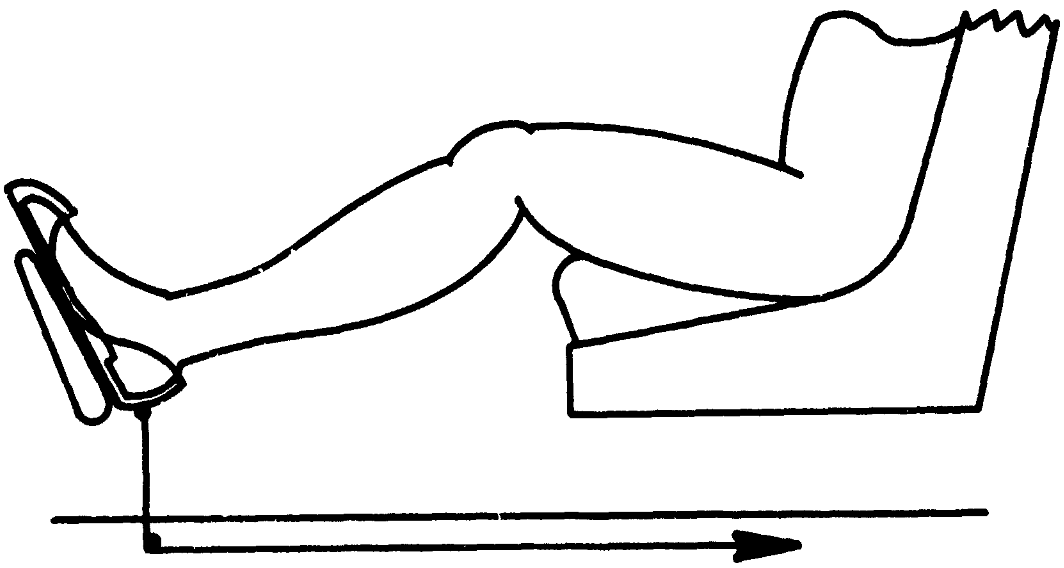


Figure 21: Pedal Attachment Retraction

that it may be possible to attach the cable to the rudder pedal. During retraction the pedal, or pedal component, is drawn toward the seat snaring the foot and positioning it against the seat. If this can be achieved, it is possible to utilize the structure of the pedal to distribute the forces over the foot and ankle.

Another adaptation of the cable concept is the system shown in figure 22. In this configuration the cable is contained in a tear-out section up the forward side of the arm and down the back of the elbow. When the system is actuated the cable pulls free from the back of the arm up to the shoulder. The segment from shoulder to wrist also pulls out and is free to draw the wrist to the chest or shoulder.

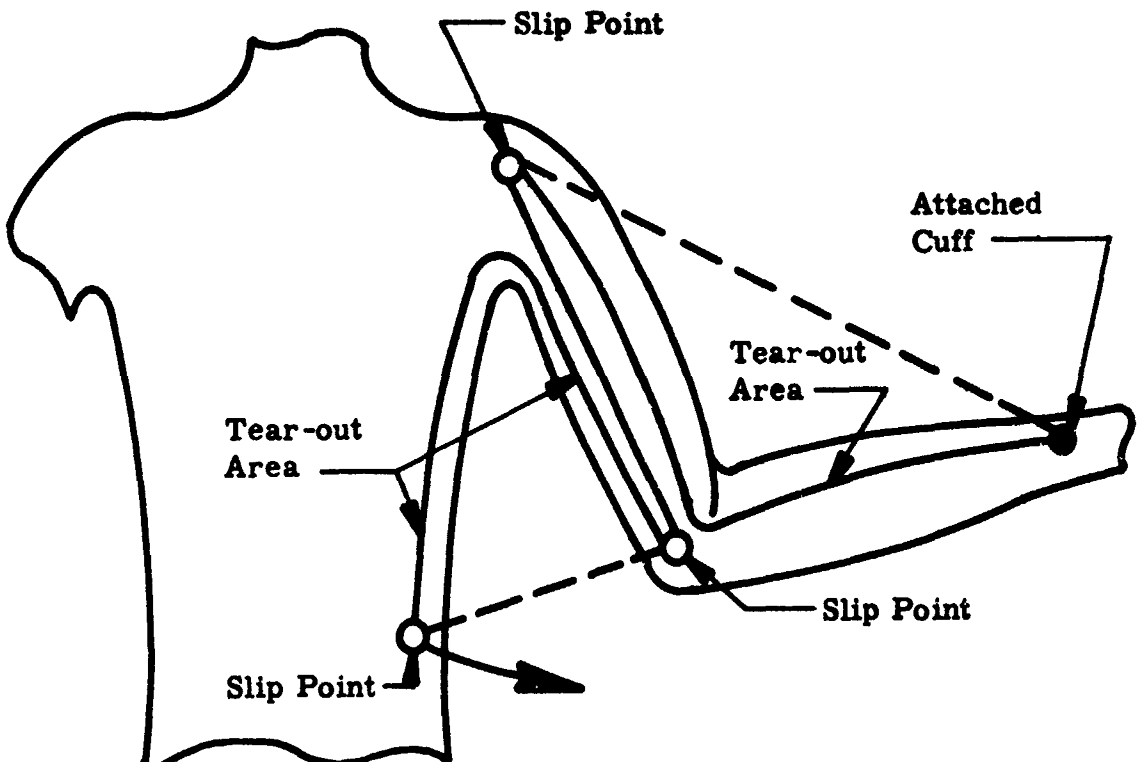
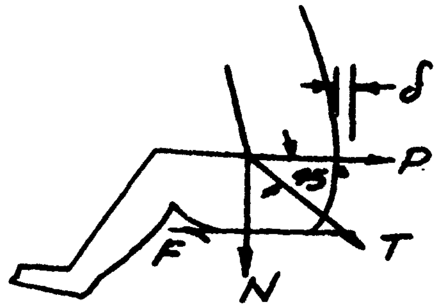


Figure 22: Arm Retraction Cable Concept

SEAT-SUBJECT INTERFACE FRICTION

One requirement of the program was examination of frictional effects. Load alleviation by frictional effects has been mentioned many times in the past. It is now desirable to investigate this as related to the present study.

Suppose we consider the retraction of the torso by use of the seat belt as shown on the following page.



The subject is seated in an ejection seat and it is desired to retract him the distance δ in a period of time t. If it is desired to apply a constant force, F, through the seat belt, the body will respond approximately as a rigid mass if the time interval is small. Assuming it is desired to retract the man 6" in 0.100 seconds, the acceleration is found from

$$\delta = \tfrac{1}{2} a t^2$$

and this requires an acceleration of 3.1 g.

Examining the figure it is apparent that at the surface of the seat the normal force is

$$N = W + 0.707\ T$$

and, therefore, the frictional force is μN. A frictional value used by Turnbow (Ref 13) is 0.7. Hence,

$$F = 0.7\ (W + 0.707\ T)$$

The net force required to achieve the 3.1 g is $P - F = 3.1\ W$ and

$$3.1\ W = 0.707\ T - 0.7\ (W + .707\ T)$$

$$T = 17.9\ W$$

Without friction $P = 3.1\ W$ $\quad .707\ T = 3.1\ W \quad$ $T = 4.4\ W$

Therefore, by having a frictional coefficient of 0.7, the tension in the seat belt must be increased by a factor of 4 to get the subject back into the seat within the desired time of 0.1 seconds.

This brief analysis points out the difference between frictional "alleviation" as usually assumed, and "detrimental" friction as is possible. In the analysis of ejection seat response it is usually

assumed that frictional effects would alleviate the forces on the human body. This is because the energy associated with the velocity change can be partially dissipated by frictional drag. However, in retracting a limb or body, the friction works against the system and causes even greater forces to be required. There are many other related aspects not mentioned in this brief study, but it is apparent that the friction at seat-subject interface will cause greater applied forces as well as higher internal loads in the body segments.

SELECTION OF CABLE TECHNIQUES FOR FURTHER INVESTIGATION

In a previous section various cable concepts were examined because of their inherent applicability to retraction and restraint techniques. At that point the objective of the study was to determine and examine techniques and not be influenced by the eventual requirement to build a test apparatus. It is necessary to examine techniques in order to be able to infer possible future systems that would have to be tested over the exposure limits of the body segments. Given that a technique is selected and fabricated, how can it be tested?

Ultimately a structural test apparatus had to be designed, fabricated, and tested with sufficient capability to evaluate future systems over the range of acceleration, velocities and applied forces that could conceivably be applied to the test subject. If a structural seat with tilting seat pan were to be used, the design criteria for the apparatus would be significantly different than the criteria for a cable positioning. It is desirable to have a device that could be used with all retraction and positioning concepts, but not practical. Therefore, because of the need to have specific strokes, forces, accelerations, and their resulting structural elements with thicknesses, lengths, pivots, pulleys, attachments, actuators, etc.; it is necessary to select some particular conceptual technique that will be the "design" technique to be considered.

The technique selected was that of applying cable elements to the body segment or restraint hardware components. Cables can transmit the forces required over large strokes, with little inertial effect, and can be directed by the use of pulleys. Hence, in retracting a segment over a given stroke it is not necessary to have elaborate structural components to interface with the segment. Nor is it necessary to design components for large inertial forces and compressive allowables. In later sections the design criteria for the desired test apparatus is dictated by cable techniques.

REVIEW OF CONCEPTS CURRENTLY BEING STUDIED

Another of the tasks of this program was to conduct a survey to determine the state-of-the-art of existing automatic body positioning and restraint devices. During this survey several notable experimental concepts were encountered. These concepts are presented here because of their basic value and for further consideration.

:

Lap Belt Tighteners

There are several lap belt tightening concepts that have evolved from the efforts of the Navy Aerospace Crew Equipment Department, Pacific-Scientific Company, and Stencel Aero Engineering Corporation.

Stencel Aero Engineering Corporation

Under a Navy contract, Stencel Aero Engineering Corporation proposed a concept that coupled the lap belt with the shoulder harness and the powered inertia reel. In this concept, shown schematically in figure 23, the shoulder harness and the ends of the lap belt are both connected to a floating link. The operation of the unit is as follows: First, the inertia reel is actuated by the escape system initiator and shoulder harness retraction begins. However, in order for the harness to retract the torso, there must be a force acting down on the floating link that reacts the retraction force. In turn, the shoulder harness force acting on the floating link must be reacted by a similar force between the lap belt and the floating link. The force between the lap belt and the floating link is only possible if the lap belt is tight and exerting a force on the crewman. Therefore, in order for any tension to exist in the inertia reel strap it is necessary for both the shoulder harness straps and the lap belt straps to be taut. If this is not the case, retraction of the inertia reel strap will cause the floating link to move freely until the lap belt and/or shoulder harness become tight. Thus, in this concept both upper torso retraction and lap belt tightening are accomplished with the same actuator.

Navy Aerospace Crew Equipment Department

During the development of the above concept the Navy incorporated several changes that would make the function more positive. As shown in figure 24, a stop was placed on the floating link to restrict its upward motion, and secondly, a stop was placed on the shoulder harness. These modifications would limit the free motion of the floating link in the event that either the lap belt or the shoulder harness would not be buckled.

The positive stop on the shoulder strap can also be used to limit lockup force. This can be accomplished by having the crewman adjust his shoulder straps with the stops against the ejection seat. With the system adjusted in this manner automatic retraction of the straps will be limited to the preadjusted tension because they cannot be retracted beyond the position of the mechanical stop.

Pacific Scientific Company

The third lap belt tightening concept is being pursued by both Pacific Scientific Company and the Navy. This concept uses a modification of the restraint harness designed by the British Institute of Aviation Medicine, which is shown in its original configuration in figure 25. In the modified version, shown in figure 26, the design of the fixed end of

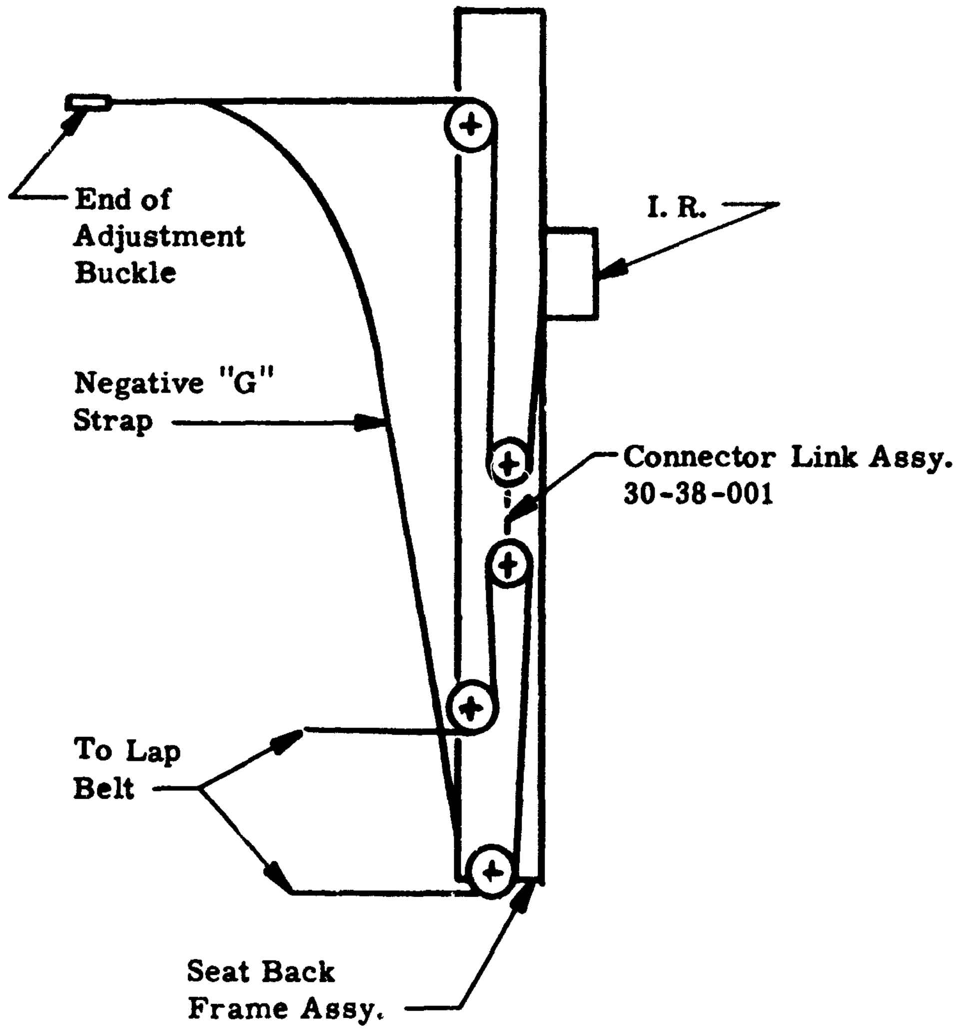


Figure 23: Stencel Aero Engineering Corporation

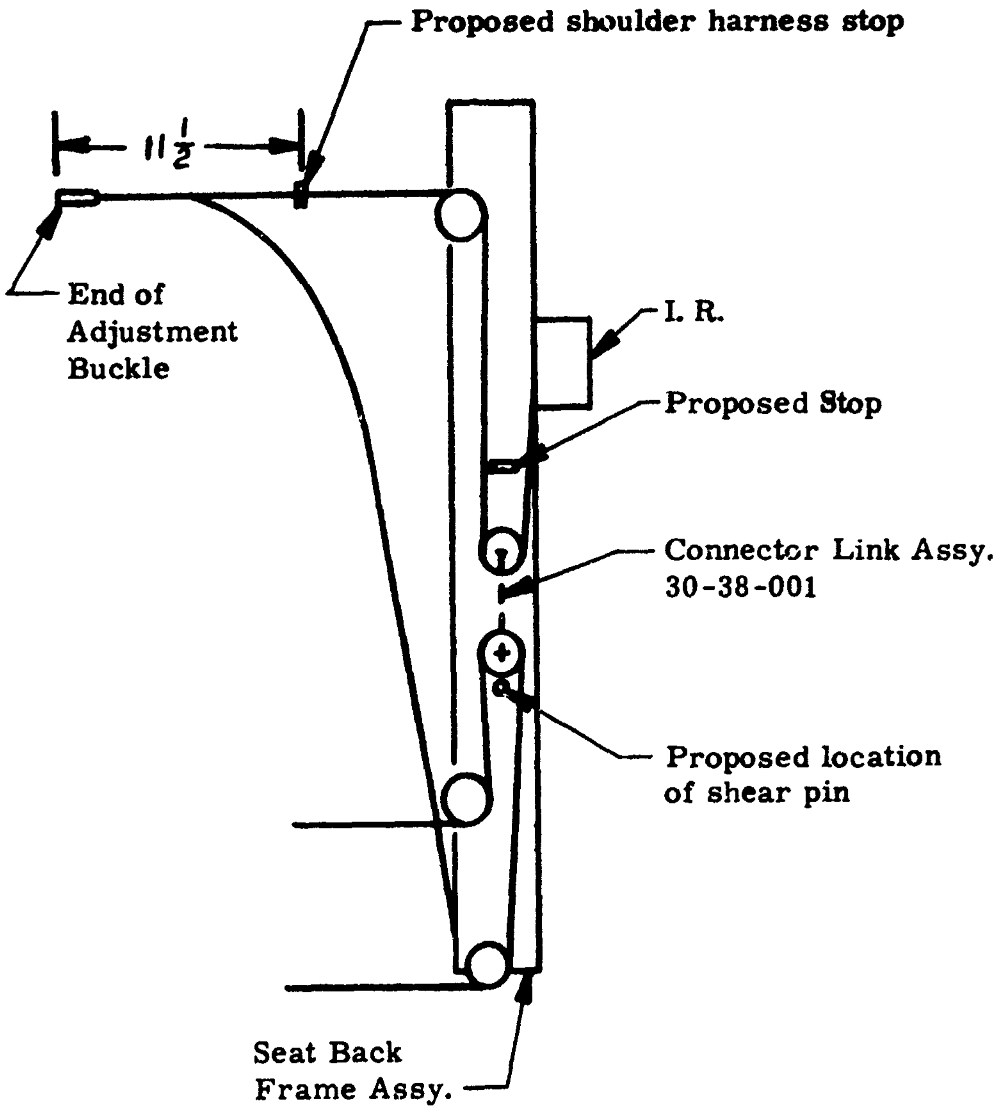


Figure 24: Navy Aerospace Crew Equipment
Adaptation

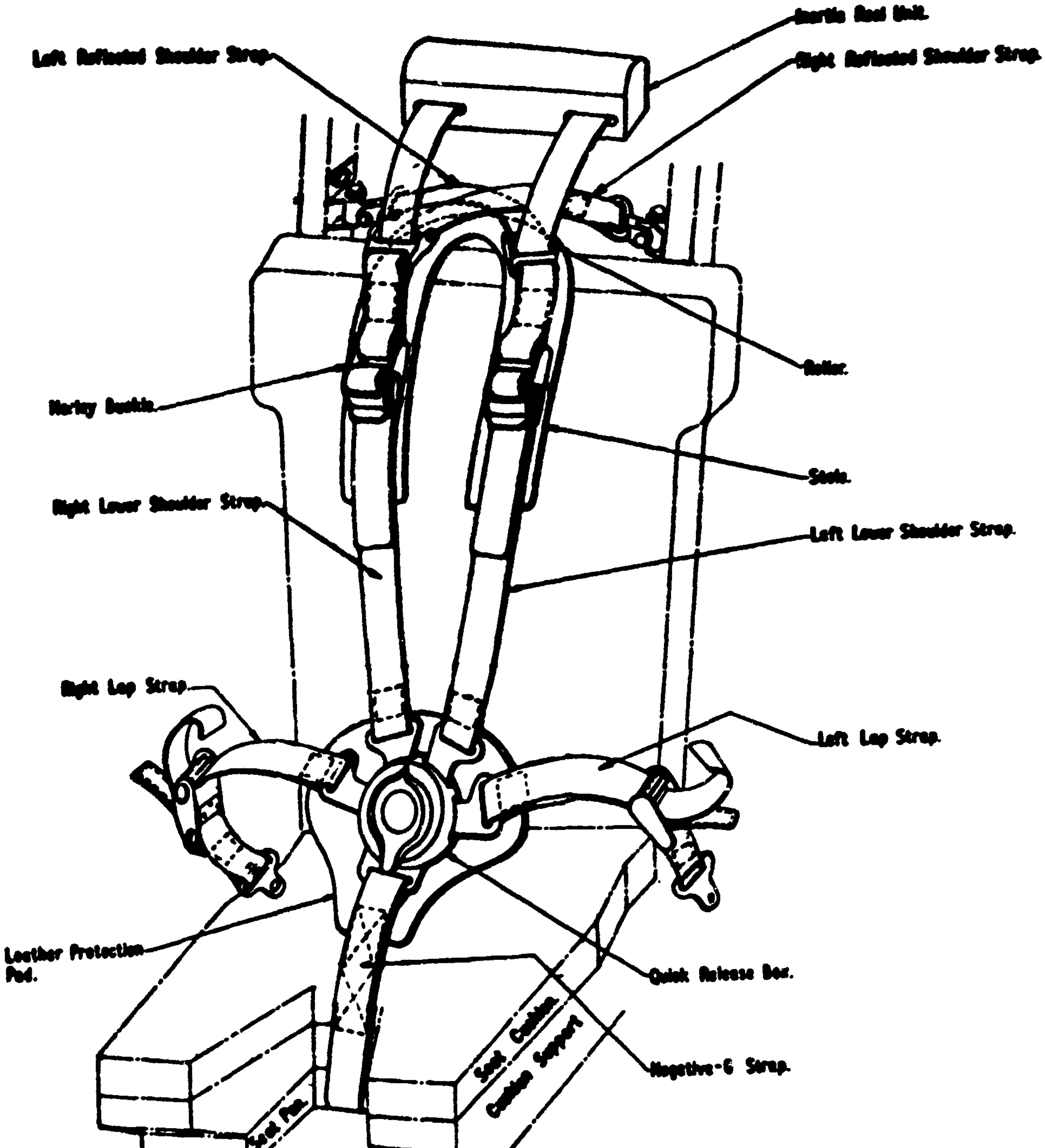


Figure 25. F-111 Seat with British I.A.M. Harness

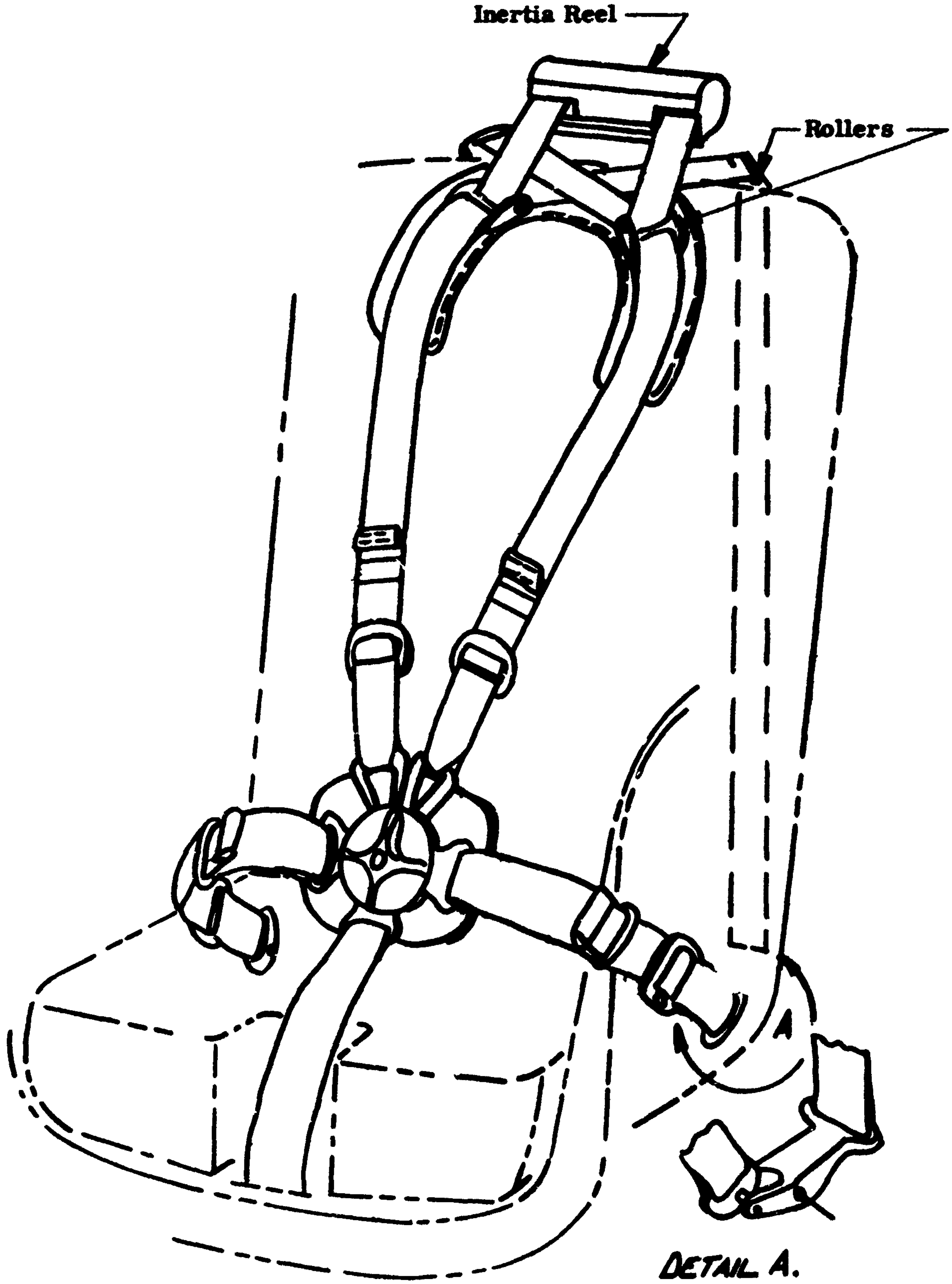


Figure 26: Modified British Harness as Proposed by Pacific-Scientific

the reflected straps is changed. The reflected strap is routed from the inertia reel over a roller in a shoulder harness. It then passes behind the neck of the crewman, across another roller, and down the back of the seat. Near the apex of the seat back and the seat pan, the end of the reflected strap is attached to one side of a bell crank. The fixed ends of the lap belt are attached to the other side of the same bell crank.

In this configuration the powered inertia reel can be used to tighten both the shoulder harness and the lap belt. When a force is applied to the shoulder harness it must be reacted by the bell crank. In doing this, it also applies a force to the lap belt. The ratio of the force between the lap belt and the shoulder harness is dependent upon the ratio of the lengths of each side of the bell crank.

Head Restraint Device

Another development worthy of note is a nead protection device that was designed by M. Schulman of the Navy Aerospace Crew Equipment Department. This device consists of a small inflatable bladder that is attached to the chin strap of a helmet. In an emergency the bladder is inflated under the chin. In this configuration the bladder prevents forward rotation of the head by filling the space between the chin ard the chest.

This device is currently under development and has undergone some human testing. The results of these tests were promising and the development is being continued.

SECTION VI

DETERMINATION OF PERFORMANCE LIMITS

The purpose of this section is to establish estimates of the test system performance parameters to insure maximum apparatus capability without causing injury to the subject. Seven parameters were selected for examination. These were: (1) retraction velocity, (2) retraction force, (3) retraction impact, (4) seat position impact, (5) retraction-positioning sequence, (6) residual force, and (7) localized impact effects.

In the following sections these parameters will be presented by listing the information from existing systems and specifications, compiling available human tolerance data, and then generating comparative results. Since the specific parameters desired are not always available, derived parameters will be presented as required. Additionally, human design criteria data not previously presented in the study report are included for later usage.

EXISTING SYSTEMS AND SPECIFICATIONS

Table III presents a compilation of the parametric values previously reported in this report. These are segregated into particular body segment parameters and not necessarily categorized as to whether or not the specification is for a seat, harness, reel or system. For specific details as to the parameter descriptions Section II should be reviewed. The presented table is to provide a quick summary of the values currently required or available.

HUMAN EXPOSURE DATA CURRENTLY AVAILABLE

A literature survey was conducted to collect information applicable to human exposure parameters. The information was collected in five anatomical subdivisions; legs, arms, torso and shoulder, head, and pelvis. Within each category the seven desired performance areas were: tolerance to mechanical motion, optimum retraction sequence, impact tolerance on rigid and flexible surfaces, mass and inertia characteristics, joint resistance and tolerance to mechanical loading.

The information desired was found in many sources. The following types were examined; conference and symposia proceedings, AMRL technical reports and journal articles. The initial source was the chronological bibliography of Impact Acceleration Stress, NAS-NRC 977. From this it was apparent that the Journal of Aviation Medicine was the most beneficial reference and all issues from 1936 were reviewed for related data.

It was apparent that some anatomical subdivisions have a large amount of published data. One example is the head, which is of great concern in head injury programs of other agencies. Another area of adequate information is mass and inertia characteristics of body segments. These are both

Table III. Performance Parameters of Current Systems & Specifications

	Upper Torso: MIL-S-9479A	MIL-D-91514A	General Dynamics B-58	General Dynamics F-111
Model Number			Stanley Aviation Corp S335022	Pacific Scientific PSCO-[illegible]03157-35
Retraction distance	18"		18"	18"
Retraction velocity	9-12'/sec	9'/sec	12'/sec	12'/sec
Retraction force	800#			900#
Retraction impact	20 g		25 g	25 g
Residual force	100#	100#	100#	100#
Retraction time	0.3 sec	0.3 sec	0.3 sec	0.3 sec

	No. American A-5	Pacific-Scientific	Talley Industries	Universal Propulsion
Model Number	Rocket Power P/N 1293-16	PSCO-0103178-1	--	--
Retraction distance	18"	18"	18"	
Retraction velocity	9'/sec, 21*	12'/sec	10'/sec	6.3'/sec
Retraction force		300#	300#	
Retraction impact	8 g, 67.3 g*	25 g		
Residual force		140#	150#	
Retraction time	.02 sec*	0.23 sec	0.3 sec	0.3 sec

Leg Retraction

	No. American A-5	General Dynamics B-58	Lockheed C-2	No. American B-70	No. American X-15
Retraction distance			30"	30"	22"
Retraction velocity	9'/sec		7'/sec**	5'/sec**	35'/sec
Retraction time		016 sec	.36 sec	0.5 sec	0.525 sec**
Retraction force			540#	480#**	200#

Arm Retraction

	No. American A-5
Retraction velocity	35'/sec, 62'/sec*

Pelvic Restraint

	Frankford Arsenal
Retraction distance	1"
Retraction force	400#

*Human test results

**Calculated

typical of directly measured data. Computer simulation studies provide indirect information in that a parameter such as joint stiffness is established by comparing computed response to observed.

All types of data were collected if it appeared that it would apply or could be applied. The sources are many and varied, and the measured responses are in terms of accelerations, forces, energies and pressures depending upon the particular investigator. The raw data is presented in Table IV.

Examination of the table indicates there is really little data directly applicable. The measurements made were not intended for design criteria purposes but rather for tolerance purposes. The table sorts the data into the applicable criteria parameters previously selected in the study program. In order to relate these to the available data it was assumed that tolerance to mechanical motion implies acceleration limits, impact on a rigid surface implies force limits, and tolerance to concentrated loading refers to pressures developed.

Great care must be used in working with the presented data. Most of it was not measured as a limb was accelerated, but rather as it was decelerated or externally impacted. Reference should be made to the original works if the numers are to be fully understood. As they are presented, they merely indicate approximations to the desired parameters.

DERIVED EXPOSURE DATA

Several other required values have been determined which are necessary for the parametric technique to be used and for apparatus design. These are mass and inertia characteristics of the body (H5) and joint resistance to flexion (H6). These have been derived from experiments conducted by many to measure cadaver response or to duplicate it.

Anthropometric and Inertia Data

The following data are compiled from several sources. The format is that of Whitsett (Ref 15) and Naab (Ref 16) and the inertial characteristics are selected to conform to the former where possible. This was done because of the moment of inertia information available from that reference. There was a variation in the data which has been noted where applicable. For those areas where the difference is not listed, comparative data were not available because of the method of data collection.

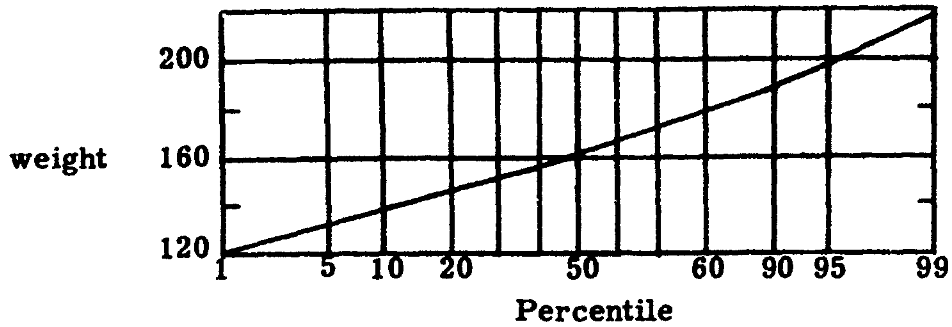
All data are referenced to the total height, total weight, and reference system presented in the first three figures. The only difficulty lies in the presentation of moments of inertia. The arms and legs have inertial characteristics that do not vary linearly with segment mass. However, it can be shown that the maximum discrepancy over the range of body weights by assuming a linear variations, will not differ from the exact solution by more than 5 percent. The moments of inertia presented

Table IV. Human Exposure Data

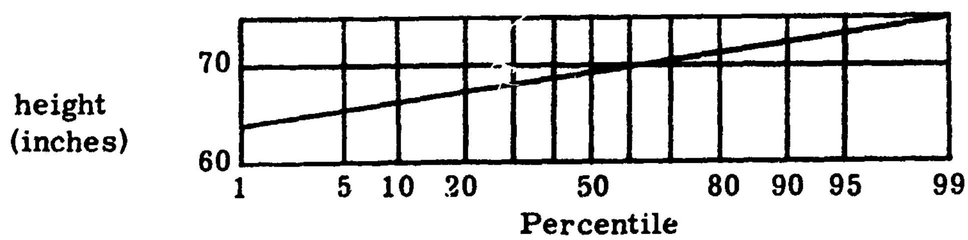
Tolerance to:	Mechanical Motion (H1)	Impact Rigid Surface (H3)	Impact Force (H4)	Concentrated Loading (H7)
1. Arms	None available	None available	None available	144# bending fracture (2)
2. Torso and shoulders	None available	None available	a. 1500# static chest load (3) b. 1190# static chest load (2) c. 5500# cadaver fracture (2) d. 5500# volunteer fracture (5)	a. 50 psi with 30 square inches of contoured contact area (3) b. 86 psi with 4 inch wide belt around thorax (5)
3. Leg	None available	None available	a. 1400# knee cap (3) b. 1000# knee cap (4) c. 233# bending failure(2) d. 1430# knee cap (2) e. 390# bending of femur(6) f. 1500# knee cap (7)	a. 470 psi over 3 square inch area on knee (3)
4. Pelvis	a. 23 g (8) b. 23 g (9) c. 19 g (10) d. 26 g (10)	a. ΔV=15.4'/sec (8) b. ΔV=36.5'/sec (9) c. ΔV=29'/sec (10)	a. 3500# belt force (8) b. 2800# belt force (9) c. 2200# belt force (10) d. 4290# belt force (10)	a. 74 psi (8) b. 52 psi (10) c. 89 psi (10) severe pain
5. Head	a. 22 g (11) b. 70-80 g (13) c. 80 g (3)	a. ΔV=5'/sec (11)	a. 1150-2000# A-P failure (12) b. 900# frontal (13) c. 400-1000# fracture(14) d. 1200# (3)	a. 900 psi (13) b. 80 psi (3)

are for the USAF mean man (height 69.11 inches and weight 163.66 pounds, Hertzberg (Ref 17)) and can be adjusted to any desired percentile by multiplication of the mass ratios.

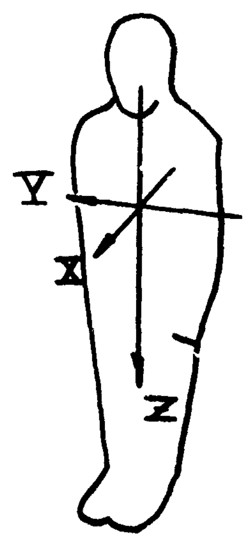
Distributions of USAF personnel by weight are shown below,



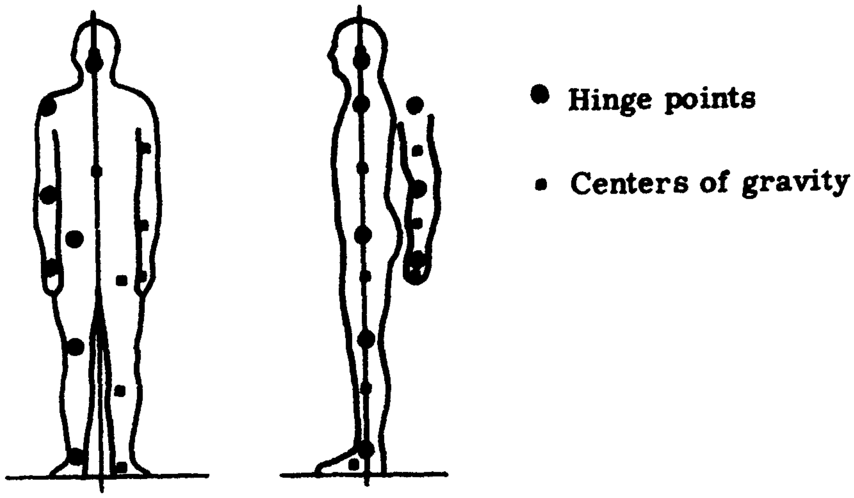
Distributions of USAF personnel by height are shown below, Hertzberg (Ref 17).



The coordinate system used in establishing dimensions and centers of gravity is shown below, Whitsett (Ref 15).



The locations of the centers of mass and hinge points are shown schematically below. These correlate with the table presented.



Coordinates of the hinge points (standing man):

Hinge Point	Percent of Total Height from Floor		
	X	Y	Z
Neck	0	0	85.5
Shoulder	0	±10.7	81.9
Elbow	0	±10.7	62.8
Hip	0	± 5.0	50.0
Knee	0	± 5.0	27.2

Coordinates of mass centers (standing man):

Mass Center	Percent of Total Height from Floor		
	X	Y	Z
Head and neck	0	0	93.5
Torso	0	0	67.8
Upper arm	0	10.7	73.5
Lower arm	0	10.7	56.8
Hand	0	10.7	45.8
Upper leg	0	5.0	40.0
Lower leg	0	5.0	17.1
Foot	3.9	6.2	2.0

The following tables present segmented parameter values which can be used in calculating the center of gravity or moments of inertia of a subject in any possible orientation.

I. Segmented Weights

Segment	Percent of Total Weight	Max Difference
Head and neck	7.3	0.6
Torso	48.1	2.0
Upper arm	6.2	1.1
Lower arm	3.7	0.5
Hand	1.7	0.3
Upper leg	20.0	1.5
Lower leg	9.8	0.2
Foot	3.2	0.2
	100.0	

II. Segment Lengths

II. Segment Lengths	Percent of Total Height	Max Difference
Head and neck (top of head to neck pivot)	14.5	2.8
Torso (neck pivot to hip pivot)	35.5	5.3
Upper arm (shoulder pivot to elbow)	18.8	1.7
Lower arm (elbow to wrist)	14.5	1.5
Hand	5.4	-
Upper leg (hip pivot to knee)	22.8	1.8
Lower leg (knee to ankle)	23.3	1.6
Foot	3.9	-

III. Segment Center of Gravity

	Percent of Segment Length			
Segment	X	Y	Z	Max Difference
Head and neck (top of head to neck pivot)	0	0	45.0	1.0 (Z)
Torso (neck pivot to hip pivot)	0	0	50.0*	10.0 (Z)*
Upper arm (shoulder pivot to elbow)	0	10.7	43.6	0.7 (Y)
Lower arm (elbow to wrist)	0	10.7	43.0	0.7 (Y)
Hand (wrist downward)	0	10.7	57.0	0.7 (Y)
Upper leg (hip pivot to knee)	0	5.0	43.3	0.3 (Y)
Lower leg (knee to ankle)	0	5.0	43.3	0.3 (Y)
Foot (ankle downward)	3.9	6.2	54.0	1.2 (Y)

*Location varies from 60 to 50 percent because of torso and torso-neck information available.

A review and compilation of existing data can be found in Human Factors, Vol. 4 (Ref 18).

IV. Segment Moments of Inertia for the USAF Mean Man

Segment	I_x	I_y	I_z
Head and neck	0.0183	0.0183	0.0123 slug-ft^2
Torso	1.0000	0.9300	0.2300
Upper arm	0.0157	0.0157	0.0018
Lower arm	0.0056	0.0056	0.0008
Hand	0.0004	0.0004	0.0004
Upper legs	0.0776	0.0776	0.0154
Lower legs	0.0372	0.0372	0.0037
Foot	0.0006	0.0028	0.0023

Adjustments to other percentiles are made by multiplying by the ratio of desired percentile weight to mean weight, 163.66 pounds. These are moments about the previously listed centers of gravity. Moments about other axes are possible by using the parallel axis equations. Various whole body configurations data can be found in AMRL-TDR-63-36, Santschi (Ref 19).

Joint Resistance to Flexion

There is a paucity of data that are related to joint resistance. In fact, no information has been found indicating tests have been conducted to measure the response of joints to transient or steady state inputs of any type. There are some related numbers available that indicate the resistance in terms of resistive torques or moments used in getting agreement between analytical models, dummies, and cadavers. Turnbow (Ref 1) has developed a computer model of seated man with joint stiffnesses that permit duplication of instrumented dummy response to full-scale dynamic tests. Patrick (Ref 20) has recorded torques required at dummy joints to produce a response similar to cadaver data. The numbers used are presented below.

	Turnbow (inch-pounds)	Patrick (inch-pounds)
Neck joint	50	7-8
Shoulder	50	7-10
Elbow	10	Locked
Hip joint	500	26-29
Knee joints	50	23-28

The torques referenced from Turnbow represent the starting moments at the joints. In the program these were coefficients multiplying functions of the angular displacement. As the angle increases and angular velocity becomes significant, an additional term was used to create a much larger resistance. This was done to generate a nonlinear joint response primarily

as a function of angular velocity. This level of sophistication is not believed to be necessary at this time, but the equations and coefficients are contained in the reference.

Fortunately, the two sets do not disagree significantly except for the hip joint. For transient inputs such as during retraction, it would seem that the body would not be able to strongly resist rotation because of the time required to stiffen the joints by muscle contraction. Hence, for design approximations it appears that 10 inch-pounds for neck and arm joints, and 30 inch-pounds for hip and knee joints should be realistic.

If it is assumed that the joints are preloaded before retraction then estimates of the joint resistance can be made by calculating the joint capability from strength and movement data of Bioastronautics Data Book (Ref 21). Arm and leg strength has been measured at various elbow and knee angles. Using the maximum force at an angle of ninety degrees, and assuming mean man dimensions yields the following maximums:

Shoulder joint moment	1700 inch-pounds
Knee joint moment	3300 inch-pounds

Tests conducted in a centrifuge provided the maximum acceleration under which the legs and neck could be lifted using muscle strength only. Again, using mean man masses and centers of gravity locations, the torques generated at the hip and neck are:

Hip joint maximum	1700 inch-pounds
Neck joint maximum	300 inch-pounds

These numbers are in the range of the dynamic stiffness coefficients proposed by Turnbow. After appreciable angular velocity develops the resistive torques were calculated using coefficients of 500 inch-pound seconds for the elbow and shoulder, 1000 inch-pound seconds for the neck, and 5000 inch-pound seconds for the hip and knee. The units are indicative that these are used with the angular velocity in radians per second.

The three selected sources indicate that there is really very little conclusive data that allow a specific number or analytical expression to be used in defining joint stiffness. The values provided by the various sources indicate that under transient conditions where the body has not had time to physiologically respond, stiffness is possibly two orders of magnitude less than joint capability. If a study is to be made analytically using joint resistance coefficients, the use of the smaller numbers would better indicate body dynamic response effects. The use of the higher number would approach the rigid mass body approximation.

COMPARATIVE RESULTS

The data available in Tables III and IV indicate that for the purpose of this program there is more exposure data from existing retraction systems test data than from biomechanical test data. The arms and legs have very little applicable data from either source. This is because there are only a few extremity retraction systems, and because biomechanical data have been concerned more with bone and joint strength than impact response. The upper torso performance data suffer from a similar problem in that data have been collected to infer crush strength and pressure limits but primarily for static tests. It is significant that a large force across the chest will crush it but this does not permit direct calculation of the forces across the chest and seat back when the torso impacts with a particular acceleration waveform.

The pelvic region is the only one where some exposure data may be obtained. Tests conducted on crash simulators and impact devices do indicate the velocity change, accelerations, and forces that were measured along with the comments of the subject. Unfortunately, where the data are best, the criteria for retraction are most difficult to specify. Is the seat belt slack, is the torso separated from the seat back? How much retraction is reasonable?

The original intent of this segment of the program was to establish exposure limit parameters to insure maximum system capability without causing injury. It now appears this cannot be done at this time. There are lower limits currently available in that test results for particular concepts do indicate particular parameter values. However, the human tolerance data do not provide the upper limits desired. Since these are not available, how can design criteria be selected? The one recourse is to revert to the results of the study phase.

SECTION VII

SYSTEM EVALUATION TECHNIQUES

Section III presented a compilation of existing retraction and restraint subsystems. In the collection of the pertinent information, data on the testing and qualification of these devices were also gathered. The techniques varied greatly and included methods from human qualification tests to tests that required a weight to be raised a given distance. Because of this diversity it is difficult to relate the results of tests on one system to those on another, or even to relate it to the human body.

Considering this, a unified testing method would seemingly yield more information from escape system development programs. If the objectives of these development programs were clearly defined and test results were completely documented, the aircraft industry could share their collective data and thus yield better systems.

The parametric flow chart presented in Section II would be useful to define the goals and objectives of a systems evaluation test program. The test planner could go through the parametric diagram to establish which parameters should be measured to evaluate the performance of a proposed positioning and restraint system.

The problem then is to establish methods that can be used to test or evaluate subsystems. Currently, human testing is often used to qualify a system. For example, the B-58 capsule systems were qualified by demonstration with a human volunteer. However, since this technique is hazardous, time consuming, and expensive, the Air Force desires to develop a system evaluation method that will eliminate the need for human testing.

This can be performed by first using a test program to establish the limits of performance for body retraction and restraint. These test results can then be correlated with mechanical simulators which are designed to simulate the dynamic properties of the human body. Such a simulator is currently being used by Pacific Scientific Company to evaluate the performance of its powered inertia reels. This device is presented as an example in the following paragraphs:

The Pacific Scientific Company Power Retraction Test Fixture (PSCo 0103692)

The Power Retraction Test Fixture, shown in figure 27, is a mechanical device designed to simulate the upper torso of a human body in an aircraft restraint harness configuration. The test fixture is comprised of a torso mass, a head mass, a simulated shoulder, a simulated restraint harness, and a means for simulating inertia loading on the torso.

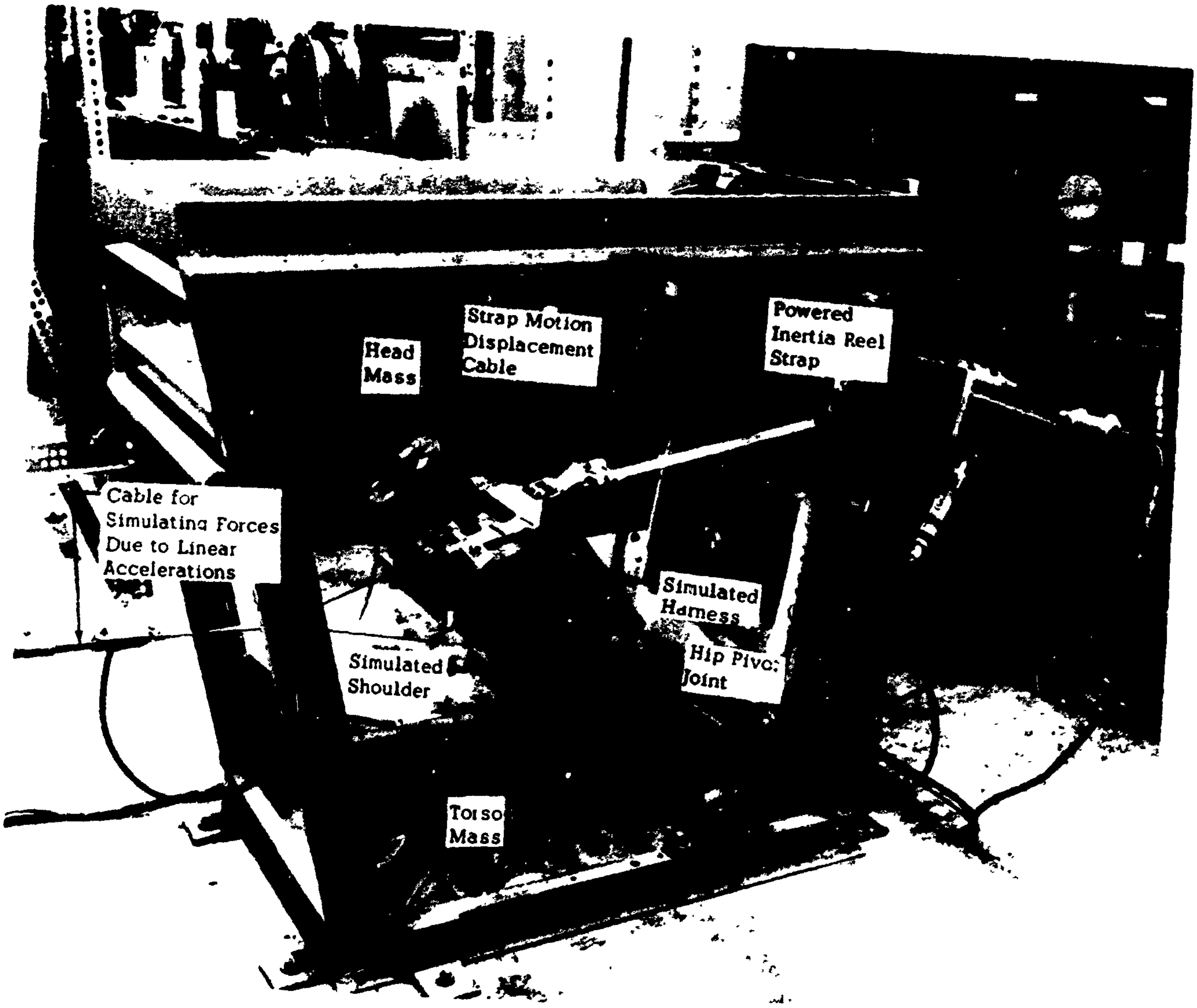


Figure 27. Pacific-Scientific Company - Power Retraction Test Fixture

The mass of the upper torso is designed so that it can be adjusted to simulate the 5th or the 95th percentile upper torso. In addition, the torso mass is pivoted about two axes to simulate bending at the hip joints and to simulate rotation of the shoulders.

Attached to the torso mass is a cable that extends to an air cylinder. This cable and air cylinder combination is intended to simulate forces caused by linear accelerations acting on the torso during an emergency condition. The air cylinder is connected to an air reservoir that can be controlled at a constant pressure. The air pressure from the reservoir acts on the tension side of the piston and thus positions the cylinder in the fully retracted position. When the simulated torso is moved from the forward position to the retracted position the cable pulls the piston against the air pressure, thus simulating a constant reaction force. The level of this force can be readily changed by adjusting the pressure in the accumulator.

The inertia reel strap, and the reaction force cable contain transducers to measure the force transmitted through each of these elements. In addition, the simulator includes a device for measuring the motion of the torso shoulder. This consists of a small cable attached to the shoulder on one end and to a spring loaded potentiometer on the other end. As the torso mass moves toward the rear, the length between the torso and the back rest shortens. This permits the potentiometer to rotate and results in a signal that is proportional to the motion of the shoulder.

Additional instrumentation provides the capability of measuring the ballistic gas pressure, the initiating nitrogen pressure, the torso chest acceleration and the capability of recording the instant of impact.

The Power Retraction Test Fixture provides the engineers of Pacific Scientific Company with the capability of thoroughly testing their powered inertia reels under laboratory conditions. Using this device they are able to test a powered inertia reel while simulating the inertia of the upper torso as well as the forces caused by aircraft acceleration acting on the upper torso. The instrumentation available permits the measurement of such parameters as retraction-time, retraction-distance versus velocity, average and maximum shoulder velocity, strap force, reaction force, ballistic gas pressure, torso acceleration, strap lockup force, etc.

Admittedly, this device responds somewhat differently than the human body. However, the difference is due to the inability to duplicate torso response accurately. Should torso biomechanics be better defined, these characteristics could be incorporated. In addition, Pacific-Scientific Company engineers have compared test results from this device with human tests and found the simulated tests result in a more severe environment

than that actually encountered by volunteers. Thus the results of the simulated tests would seem to be conservative in that the restraint system components must sustain greater forces and accelerations.

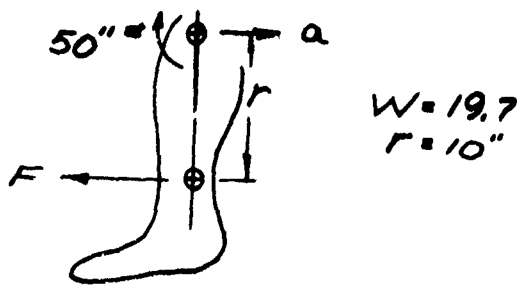
Talley Industries has used a test setup that is very similar to the Pacific Scientific Company device. The major difference was the Talley Industries engineers used 5th and 95th percentile anthropometric dummies to simulate the human torso.

In retrospect, the concept of these test setups seem to be quite satisfactory for testing and qualification of prototype and production equipment. One function that mechanical simulators cannot perform is the establishment of exposure limits for the human body. However, these values can be established in carefully controlled laboratory experiments specifically designed to establish the limits of the human body for automatic body positioning and restraint.

Thus, a recommendation of this study would be to incorporate the use of body simulators for evaluating and testing body positioning and restraint devices.

These simulators can be rather simple if only one body segment is being considered or can approach the complexity of an anthropometric dummy when more than one body segment is being considered. However, the design of these simulators should not be treated lightly. Most current anthropometric dummies would not be adequate for testing retraction systems for the arms and legs. The reasons for this are that the joint kinematics are not truly representative of joint motion and that there is little known about the simulation of joint stiffness.

In order to investigate the significance of joint stiffness a few calculations were performed. First consider the knee joint. According to the references cited in Section III, the joint stiffness of the knee should be in the range of 50 inch-pounds. Now, if the lower leg is pivoted at the knee as shown below, what acceleration (a) is required to overcome the joint stiffness at the knee joint?



Assuming the distribution of a 95 percentile man, the weight of the lower leg is approximately 19.7 pounds and its center of gravity is approximately 10 inches below the hinge point of the knee. If the stiffness of the knee joint is of a frictional nature it will resist torques up to 50 inch-pounds and then motion will occur. Under these assumptions compute the value of "a" required to cause rotation of the lower leg.

$$T = 50 \text{ inch-pounds} = F \cdot r = m \cdot a \cdot r$$

$$a = \frac{50}{mr} = \frac{50}{\frac{19.7}{32.2} \; .10} = 8.3 \text{ ft/sec}^2$$

This indicates that the joint resistance of the knee will only resist a very small level of acceleration. Therefore, it would seem that the joint stiffness of the knee can be neglected in the design of any simulator to test lower leg retraction devices. The design requirements could then be restricted to the simulation of mass, inertial and kinematic characteristics. Similar conclusions can be drawn about the elbow and shoulder joints.

SECTION VIII

EXPERIMENTAL REQUIREMENTS

The results of the previous sections indicate that there is a great need for experimental data to be collected for several of the body segments. These can be tabulated as below:

Torso - Tests should be run to measure shoulder impact velocity and force response and correlate with subjective tolerance. During such tests the retraction forces should be measured to obtain force data as well as torso inertia data.

Legs - Concentrated loading data are required on the legs. These data can be collected during acceleration and impact studies. The response on rigid and elastic surfaces are required.

Arms - Tests similar to the leg type tests should be conducted in addition to impact studies on the chest.

Pelvis - Force measurement tests are required to define the relations of force and snubbing length required to retract the man.

Head - The tests necessary for head retraction cannot be specified at this time since the head response is relative to the shoulder motion and not relative to the seat. However, upper torso tests at large torso retraction velocities will permit examination of head response due to torso motion and this information is extremely desirable.

The list of needed data is very extensive but it is possible to satisfy these requirements if we consider the design of the test apparatus as dictated by previous assumptions. That is, if the design is based upon the utilization of cable devices, it is only necessary to consider the maximum retraction distances determined and assumed retraction distance. The inertial, mass and anthropometric data are known and joint resistance effects can be assumed negligible. Therefore, the forces of the test apparatus required can be calculated. The only remaining design criteria is that of assuming that the device must be capable of testing the 5th through 95th percentile man in a seat that will be compatible with ejection seat and ejection clearance limits.

Estimates of the forces required for limb and torso retraction were calculated assuming rigid body response. The calculated values are presented in the Appendix.

The results shown are for 0.1 second retraction time.

Torso	750 lb.
Leg	110 lb.
Arm	57 lb.

With this information available it was possible to examine approaches to the design of the test apparatus.

FEASIBILITY STUDY

From the above data it was determined that for the test system the maximum distance of retraction should be 30 inches and that the system should be capable of a retraction time of 0.1 second. The force requirements for the test system were determined from data taken on the leg. The initial figures used for the leg were 200 lbs. applied force plus 40 lbs. inertial load, which comes to approximately 500 lbs. when multiplied by a safety factor of two. This is quite acceptable with the 110 lbs. later calculated.

Since the distance of 30 inches was felt to be too long for an actuating device to travel, the distance was reduced by one-half by a belt and roller device, as shown below.

By reducing the distance requirement, the velocity is decreased and the force is increased; and the final design criteria were a force of 1000 lbs. and a velocity of 150 in/sec.

Systems Considered

Using the above criteria as the worst case, two types of systems for retraction were considered. One was a hydraulic system and the other a mechanical system. It was felt that these two types of systems offered the greatest possibility of success due to the existing hardware that is available.

The hydraulic system uses a hydraulic cylinder to perform the retraction. Control of the cylinder is accomplished by a solenoid valve. Fluid to operate the hydraulic cylinder is stored in an accumulator, and the accumulator is charged by a pump drawing fluid from a reservoir. A pressure compensated flow control valve is placed in the system to maintain constant velocity. If a constant force is required, this valve can be shunted by a by-pass valve. This is shown schematically in figure 28.

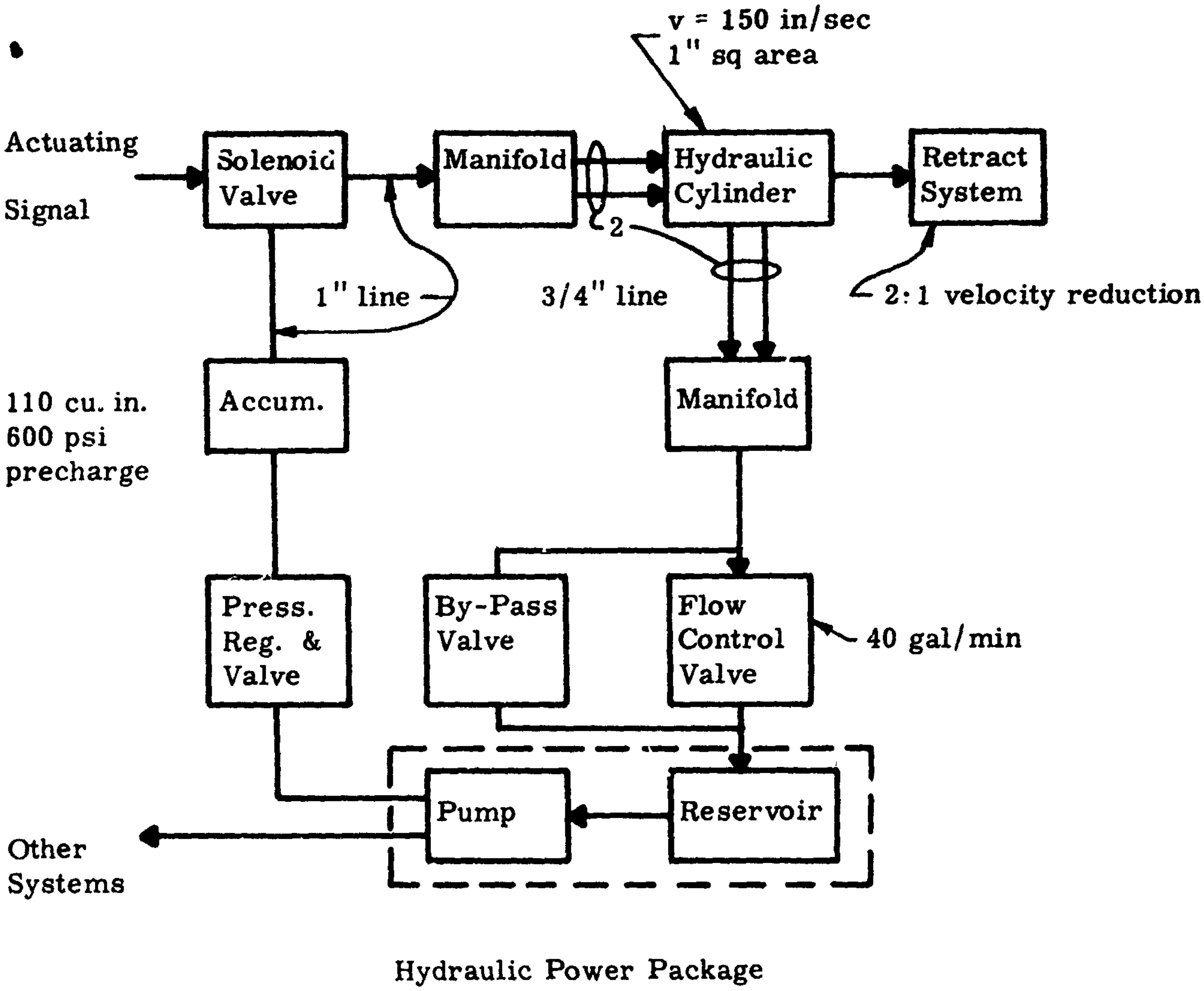


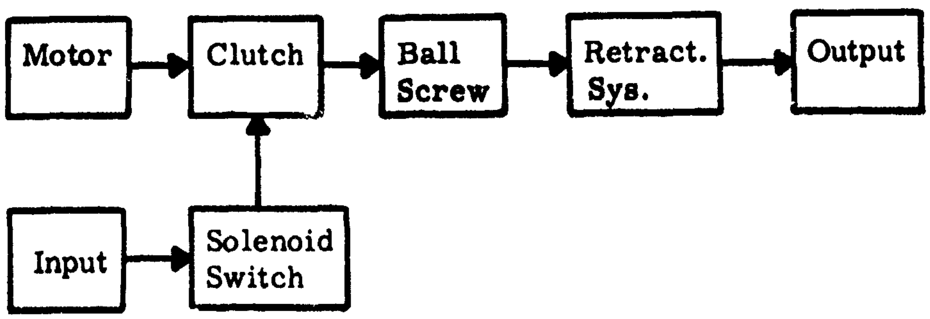
Figure 28: Hydraulics System Schematic

The requirement that the retraction time be 0.1 second and distance of 15 inches means that the velocity of the cylinder piston has to be 150 in/sec or 750 ft/min. By assuming a piston area of one square inch, the pressure must be 1000 psi and the volume flow rate must be 150 cubic in/sec or approximately 40 gal/min. This flow rate can be controlled by a 0-40 gallon flow control valve which is placed in the exhaust side of the cylinder. The amount of fluid required to operate this system is 15 cubic inches, and this quantity is stored in a 116 cubic inch (total) accumulator at 1300 psi operating pressure. The accumulator pressure of 1300 psi is required to provide a system operative pressure of 1000 psi. This information is shown schematically in figure 28. The requirements listed can be met by commercially available components.

The requirements of this system place extreme demands on two components of the system. One possible problem area was the hydraulic cylinder. Because the high velocity required by this cylinder, it would have to be a special built model. However, it appeared that a special cylinder could be built that would meet the needs of the system without excessive cost. The other possible trouble area was the time response of the pressure compensated flow control valves. Since the time requirement is so short (0.1 second), it was questionable whether pressure compensated constant flow could be obtained.

If the above problem areas did materialize, there were some alternate choices available. The speed of the cylinder could be reduced by going to a linkage arrangement to gain a mechanical advantage and reduce the velocity. Another approach was to increase the time requirement from 0.1 second to 0.2 second. This would reduce the velocity required by a factor of two, the forces by a factor of four, and improve the possibility of obtaining constant flow.

Retraction is performed in the mechanical system by a motor driven ball screw. Actuation of this device is accomplished by a solenoid operated clutch. The ball screw and motor used in the system is determined by the velocity requirement. By knowing the velocity has to be 150 in/sec or 9000 in/min and assuming a thread pitch of 0.1, the ball screw and motor speed was found to be 90,000 rpm. The horsepower of the motor required to operate the ball screw is 17 hp. These are shown below:



Both the high rpm and relatively high horsepower necessary for operation present a problem for this system. These demands require that the motor, ball screw, and clutch will have to be special units. The horsepower requirement indicates that the system does a certain amount of work in a specified time. If the time is doubled (to 0.2 second), the force is reduced by a factor of four, and the horsepower is reduced by a factor of eight. Also, the speed could be reduced by having the ball screw drive a linkage arrangement.

Systems Study

The two systems described above were the only types of systems felt to be feasible. Of these two systems, the most promising was the hydraulic system. All the hydraulic components, with the exception of the cylinder, were readily available and the cylinder could be a special built unit. On the other hand, in the mechanical system there are three components of the system which would have to be special built. These are the ball screw, motor, and clutch, and they would be special items even if the time requirement were changed to 0.2 second. Another disadvantage to the mechanical system is the effects of friction and mass of the system which has not been included. Therefore, the hydraulic system was selected as the one to be developed.

STRUCTURAL DESIGN

The structural support is shown in figure 29. The figure is a scale drawing and the hydraulic units shown are dimensionally representative of commercially available units. The following paragraphs supply the description of the aspects considered in developing the structural design.

Restraint System Components

The four restraint systems are composed of the various harness, seat belts and the like, which are actuated by the hydraulic system. The hydraulic actuators are rigidly mounted to the support frame. Cables which pass over a series of pulleys to apply the desired force on the restraining straps are secured to the actuator piston.

One shoulder restraint actuator and two arm restraint actuators are located in back of the seat on the test fixture in tandem. Similarly, one torso restraint actuator and two leg restraint actuators are placed below the seat in tandem. Each actuator has an accumulator located immediately adjacent to it. The power supply is mounted in back of the seat and low on the frame to aid in obtaining a low center of gravity and increased damping.

Where required, additional support for the hydraulic controls and tubing will be added to provide a secure system free from excessive vibration.

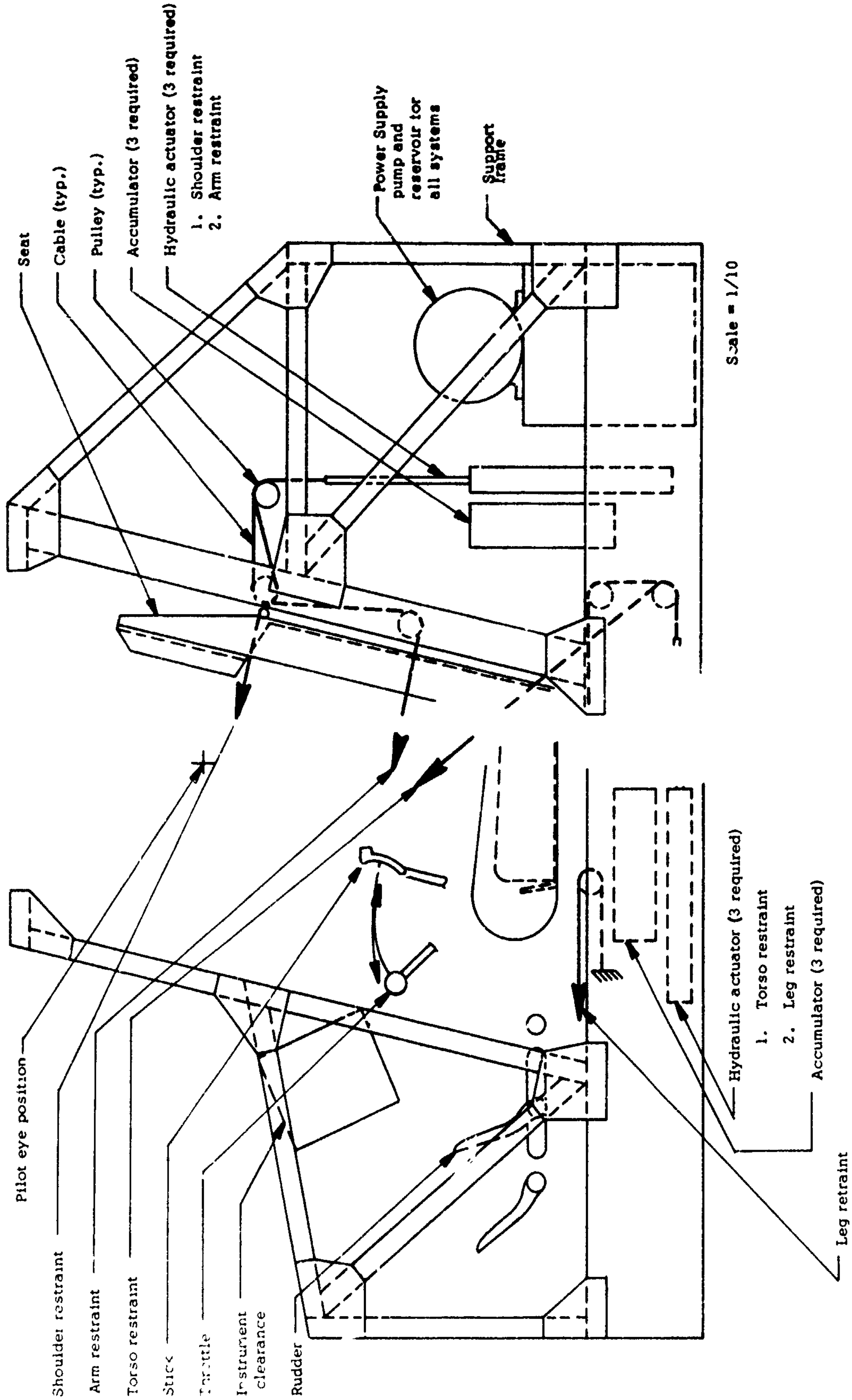


Figure 29: Test Apparatus Support Structure

Cockpit Simulation

Provisions were considered for cockpit control simulation in the test apparatus. Thus for certain test procedures the subject would be able to assume specified positions for hands, arms and feet. The throttle quadrant, rudder, stick and instrument panel and their relative size and position conform to AFSCM 80-1. It is not necessary that simulated components be designed for severe loads since they should not be subjected to any appreciable loads during retraction. The criteria used here would primarily require that normal or expected usage will not cause failure.

Seat Configuration

The simulated ejection seat that is permanently installed in the test rig meets the dimensional requirements of MIL-S-9479A and is adjustable vertically ±2.5 inches. Since it is not the purpose of the experiments to be performed on this test apparatus to verify the strength of the seat, it is sufficiently overdesigned to prove capability by means of analysis alone. Thus the seat is greater in weight and strength than an airborne ejection seat. The ejection track and all other related appurtenances have been deleted from the design for this test. Their added weight, cost and complexity serving no useful purpose.

External Frame

The structure is a bolted frame made up of steel angles and channels joined with gussets and clips. The loads developed by the hydraulic restraint system are reacted internally by the support frame. Bracing members are used to distribute loads and attach operating equipment. The development of an internally-reacted load-carrying unit will permit easy movement of the apparatus to desired areas for testing purposes.

The rigidity and weight of the test apparatus is efficiently utilized to absorb the shock developed by the actuating cylinders. A ballast box may later be built into the frame and filled with gravel for additional damping if desired.

SECTION IX

AUTOMATIC RESTRAINT AND BODY POSITIONING APPARATUS

The final efforts of the program were the final design, fabrication and qualification testing of the Automatic Restraint and Body Positioning Apparatus. A hydraulic system had been shown feasible to actuate the system, a structural frame could be provided to support the system, and that the device could be used to measure human response as well as evaluate restraint and positioning systems. The remaining steps were to generate operational hardware.

HYDRAULICS SYSTEM

Several hydraulics systems manufacturers were contacted and provided with the preliminary hydraulics schematic of figure 28. Along with the schematic performance specifications were listed as:

Velocity	150 in/sec
Force	1000 pounds
Stroke	15 inches
Stroke Duration	0.1 seconds
Volume Flow Rate	39 gallons per minute

for both arms and legs, and

Velocity	180 inches/second
Force	1000 pounds
Stroke	18 inches
Stroke Duration	0.1 seconds
Volume Flow Rate	46 gallons/minute

for the upper torso, and

Velocity	45 inches/second
Force	1000 pounds
Stroke	18 inches
Stroke Duration	0.1 seconds
Volume Flow Rate	12 gallons/minute

for the lower torso.

Initially there was some difficulty in obtaining any data relative to retraction time of hydraulic actuators. And in fact, no guarantees were ever provided assuring a retraction time of 0.1 seconds. A simple analog circuit of fluid inertance, resistance, and constant pressure input was analyzed for an assumed 1000 psi, line length of 160 inches

and desired flow rate of 150 cubic inches per second. A value of 0.056 seconds was calculated for the time to reach 90 percent of full flow. This, along with manufacturers assurances that the time could be achieved with adequate pipe size, led to purchasing of a hydraulic system from Pabco Fluid Power Company, Cincinnati, Ohio. The schematic is shown in figure 30.

The supporting structure was designed to provide adequate rigidity and strength for all loading conditions generated by the actuators acting simultaneously. Structural steel shapes were selected because of low cost and availability. Complete structural drawings were provided to the Aeronautical Systems Division Shop and fabrication and hydraulics installation were accomplished at that site.

SAFETY CONSIDERATIONS

Several design aspects were dictated by safety considerations. The electrical control circuit, figure 31, has the capability to incorporate a remote test switch such that no power can be applied to the solenoid valves until it is closed. The structural is physically designed so that all high pressure elements are separated from the man by a structural seat, seat support and floor. Any high pressure failures will be absorbed by the intervening structure.

The retraction displacement limits of the segments were also examined to determine possible dangers in attempting to pull the segment too far into the impact surface. The cable travel is dictated by the stroke of the actuator which bottoms on a cushion within the actuator. Therefore, unless there is a failure of the actuator, the segment can only be retracted by the length of the hydraulic stroke. The displacement of the cable is limited by the length of the cable from actuator to body segment. The impact surfaces are capable of being adjusted along the segment travel. By stroking the actuator to its limit and then attaching the impact surface to the floor, the limb cannot be retracted beyond the level desired into the impact surface.

Initially, limb positioning was a problem in that with only high pressure available to the selector valves, as originally planned, large accelerations would have been experienced during positioning. The final design permits pump pressure to be used in adjusting segments slowly.

The system is designed to operate at 1000 psi as dictated by the flow through the system and inertial accumulator pressure. Should the pressure sensitive switch fail to operate, the motor is fused for an electrical equivalent of pumping against 2000 psi. The pumping therefore, stops before reaching the 3000 psi allowable.

QUALIFICATION TESTING

The final system as tested is shown in figure 32. Tests were required to

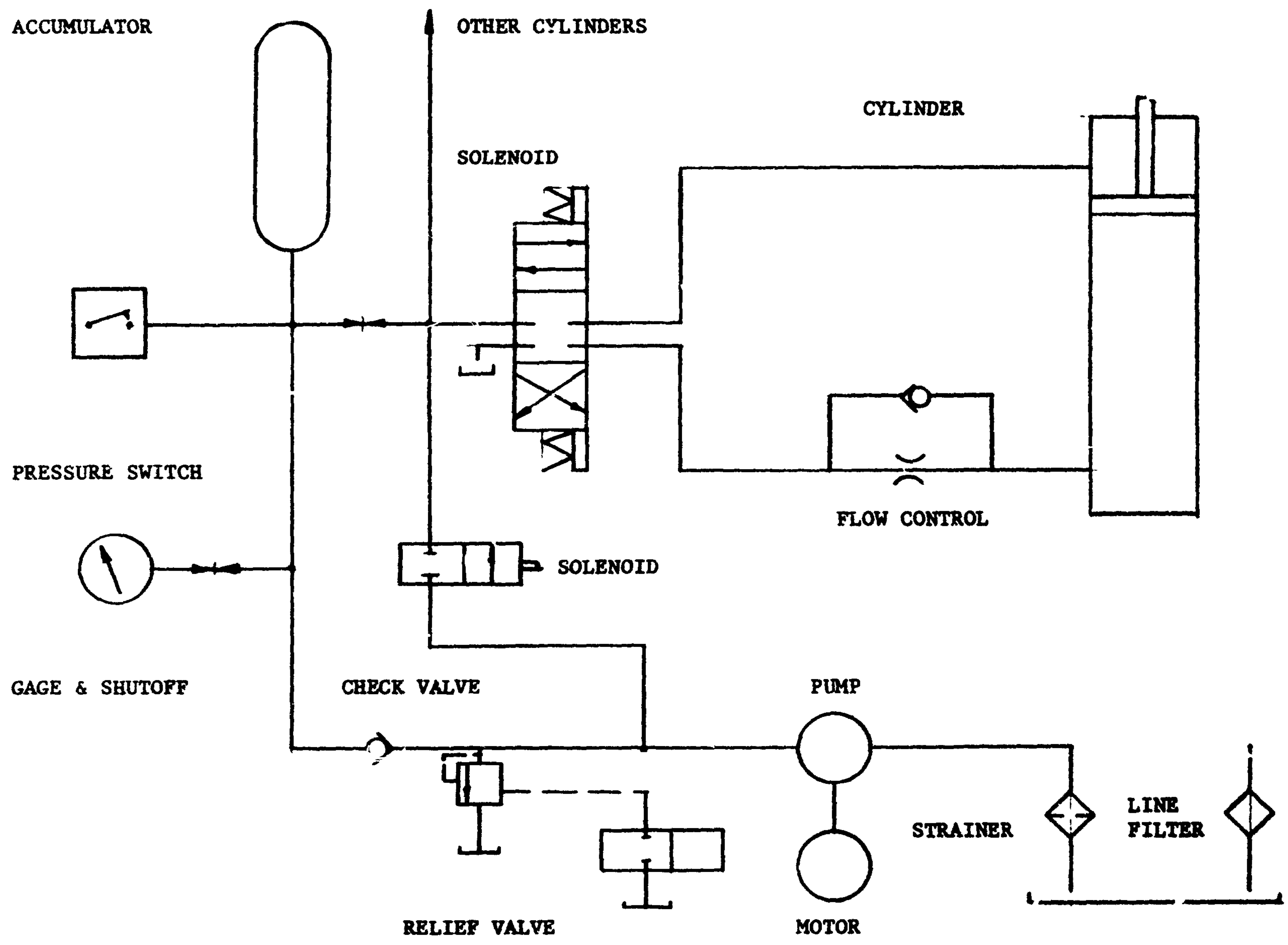


Figure 30: PABCO System

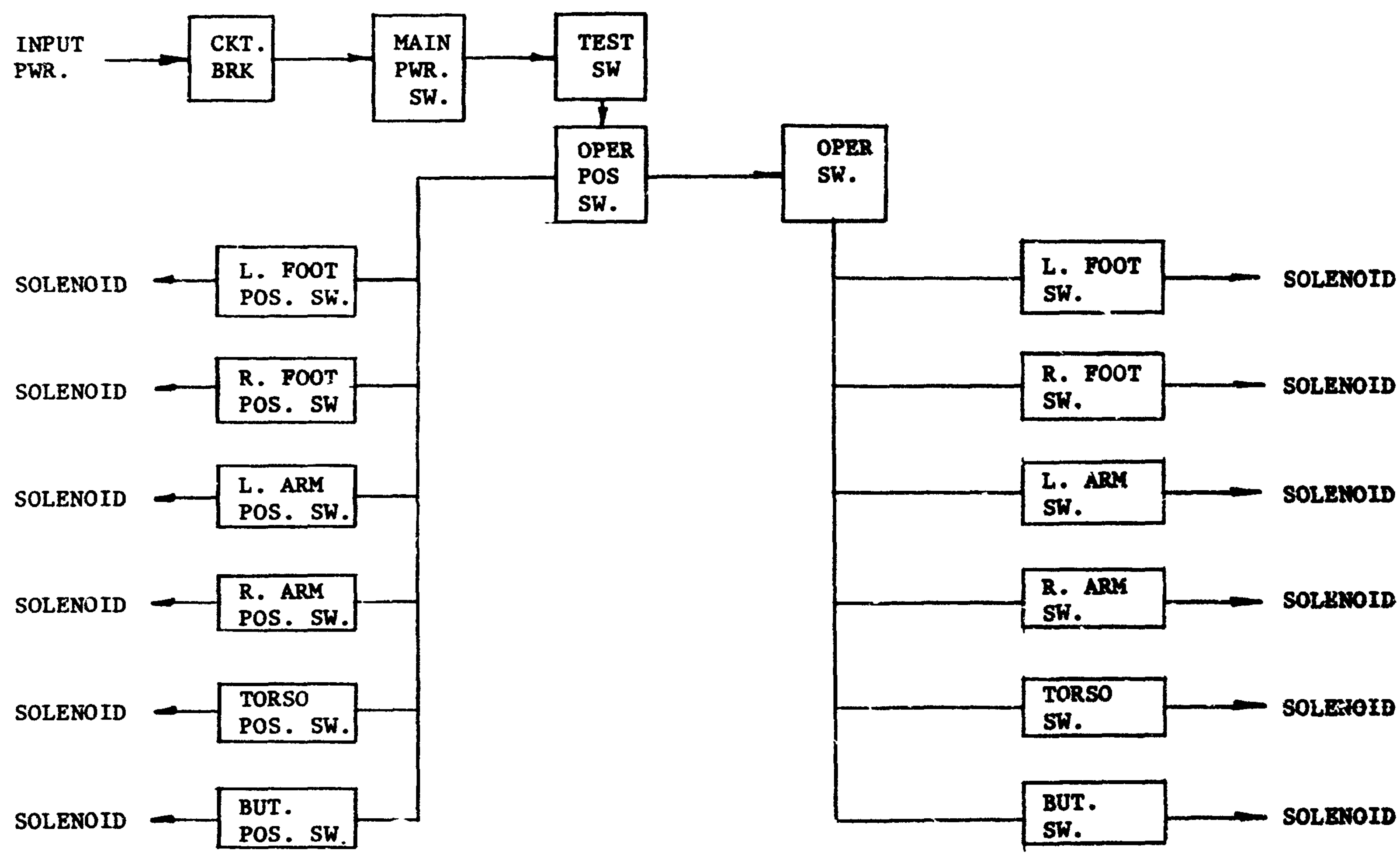


Figure 31: Hydraulic Control Subsystem

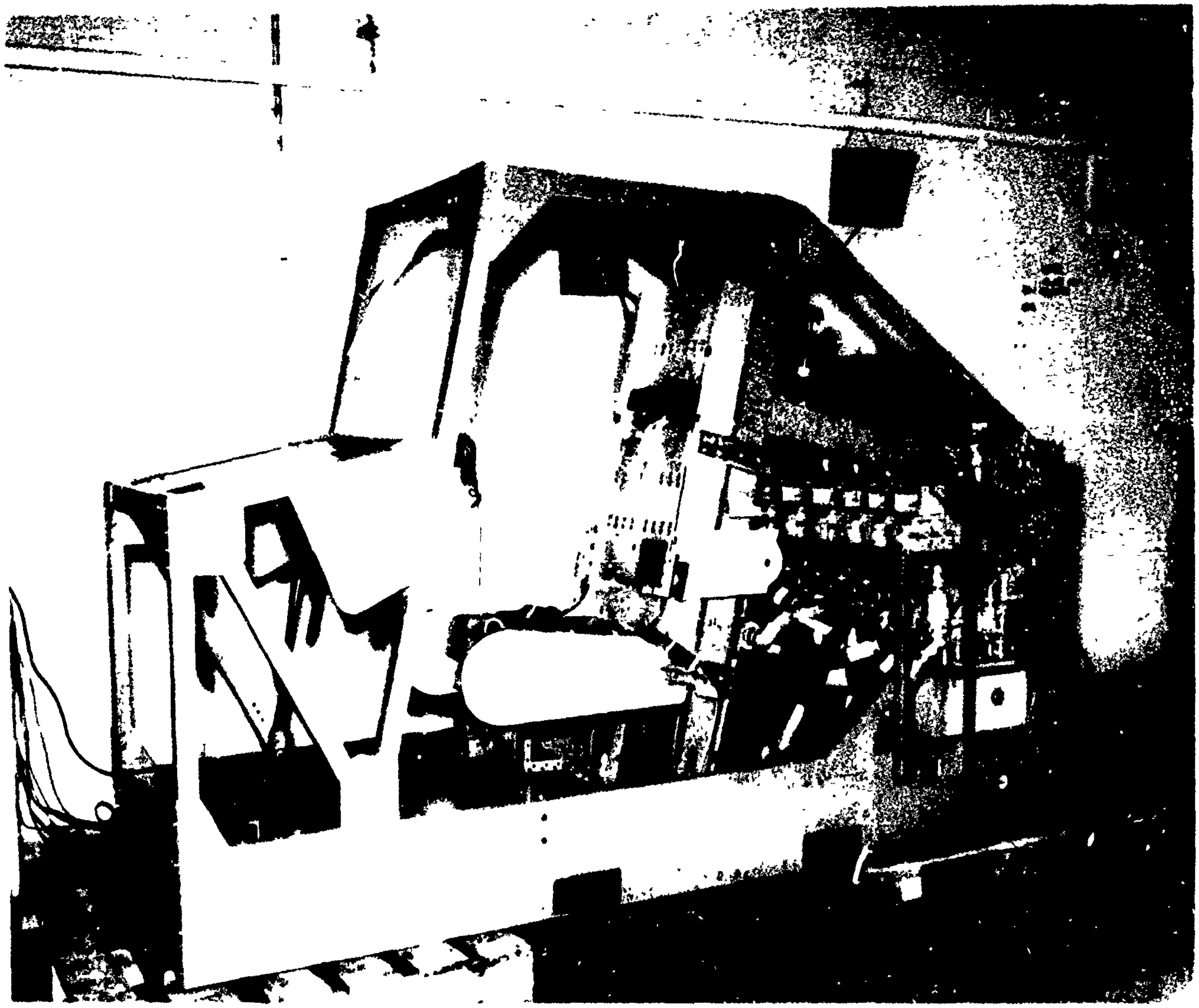
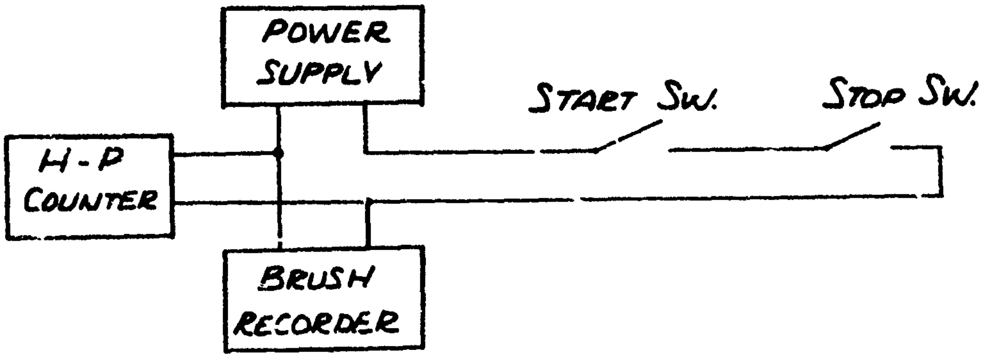


Figure 32. Automatic Restraint and Body Positioning System

demonstrate that the actuators would retract over the desired strokes within 0.100 seconds. A simple test schematic as shown below was used for the test.



The tests conducted at maximum stroke lengths resulted in an average retraction time of 112 milliseconds for all with a maximum of 144 milliseconds for the upper torso and 89 milliseconds for the right foot. Additional tests were conducted at retraction lengths slightly less than the maximum, 14.5 inches instead of 15, and a significantly shorter time observed, 91 milliseconds. This led to the observation that the extreme limits of the stroke are greatly influenced by the hydraulic cushions at the ends of the rods. These are provided to limit the deceleration forces developed at the ends of the strokes.

All tests were conducted at an accumulator pressure of 950 psi under no load. These conditions were acceptable for purposes of qualifying the apparatus and the device was accepted based upon the test results.

SECTION X

CONCLUSIONS AND RECOMMENDATIONS

Several conclusions have been drawn from the research:

1. It has been possible to select parameters that are required to design automatic body positioning and restraint systems, and to establish the relationship that exists between them. The relationship was pictorially established as a parametric flow diagram to aid in visualizing the interdependence of the system parameters.

2. Existing retraction and retentional subsystems are designed to meet current specifications and not necessarily to minimize time of retraction. Upper torso retraction is currently accomplished within 0.3 seconds and human tests have been conducted within much less time. Legs have been retracted in less than 0.1 seconds under laboratory conditions. Only one arm retraction system has been developed and large (62 ft/sec) velocities were achieved with human subjects. Head and pelvic retraction data are virtually nonexistent.

3. The prepositioning time required is a function of the escape system. If the system is restrained by limitations due to canopy ejection and pyrotechnic variability, then it is improbable that prepositioning has to occur in less than 0.2 seconds. However, if a crew escape module or ejection through the canopy is considered, the time is more probably 0.1 seconds.

4. No data are available on the effects of prepositioning sequencing.

5. The concept of cable retraction of body segments was selected as the most acceptable means of future study of body retraction.

6. The exposure data available from human test results were not sufficient to establish limiting valves of the design parameters desired. Some information is available from retraction systems tests. The existing and related biomechanics data do not significantly improve the situation.

7. There have been some devices used to evaluate restraint system components. These permit tests which have satisfied the requirements of specifications, but cannot be improved to meet realistic retraction requirements until a better understanding of human response and limits is established.

8. A hydraulically activated, cable-rigged, test apparatus was designed, fabricated and tested which will provide the capability to test human subjects with minimum retraction times and maximum distances compatible with current escape capsule criteria. It is anticipated the capability of the device will

provide environment of greater severity than those permitted by human tolerance.

The conclusions lead to the following recommendations:

1. The automatic retraction and body positioning device should be fully instrumented and operated over a wide range of retraction times and distances to measure a consistent set of parameters usable by restraint system designers. Current data are incomplete in that not all parameters are accurately measured. By using the apparatus as designed it is possible to evaluate the effects of initial retraction acceleration, initial force, retraction velocity and displacement, impact acceleration, impact velocity, impact force, and impact surface characteristics. These can be evaluated relative to subjective response.

2. Because of the data that will be available, biomechanical data should be calculated from the measured parameters. That is, joint stiffness in particular can be accurately evaluated because of the wide range of the retraction environment possible. This data could then be used for future design criteria.

3. The apparatus should be updated to permit sequencing of body segments. Tests conducted on single body segments provide pertinent data, but to evaluate the "optimum" retraction, if it exists, it is necessary to determine the effects of simultaneous and sequenced retraction.

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